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NATIONAL COMMUNICATIONS SYSTEM

AERIAL T1 EMP EFFECTS ASSESSMENT VOLUME I

MAY 15,1987

OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
WASHINGTON, D.C. 20305

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The Office of the Manager, National Communications System (OMNCS) has undertaken the Electromagnetic Pulse (EMP) Mitigation program to support the survivability objectives addressed by National Security Decision Directive 97 (NSDD-97) and Executive Order 12472. The objective of this program is to mitigate the damaging effects of nuclear weapons on regional and national telecommunications capabilities. To meet this objective, the OMNCS has sponsored efforts to create a network-level model to assess the effects of high-altitude EMP (HEMP). In addition, th OMNCS has sponsored various efforts to collect the system-level HEMP effects data required to support the network-level model. The products of this model assist the NCS in identifying potential vulnerabilities of national telecommunications capabilites to HEMP and supporting National Security and Emergency Preparedness (NSEP) initiatives. This report presents an assessment of the survivability of aerial T1 systems in a HEMP environment. This effort include a test program to collect the data required to assess coupling of incident electromagnetic field to aerial T1 cables. Also this report documents the test activities and the data collected. It also reviews the results of the buried T1 system assessment and summarizes the relevant (cont

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EXECUTIVE SUMMARY

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The Office of the Manager, National Communications System (OMNCS) has undertaken the Electromagnetic Pulse (EMP) Mitigation program to support the survivability objectives addressed by National Security Decision Directive 97 (NSDD-97) and Executive Order 12472. The objective of this program is to mitigate the damaging effects of nuclear weapons on regional and national telecommunications capabilities. To meet this objective, the OMNCS has sponsored efforts to create a network-level model to assess the effects of high-altitude EMP (HEMP). In addition, the OMNCS has sponsored various efforts to collect the system-level HEMP effects data required to support the network-level model. The products of this model assist the NCS in identifying potential vulnerabilities of national telecommunications capabilities to HEMP and supporting National Security and Emergency Preparedness (NSEP) initiatives.

This report presents an assessment of the survivability of aerial T1 systems in a HEMP environment. This effort includes a test program to collect the data required to assess coupling of incident electromagnetic fields to aerial T1 cables. This report documents the test activities and the data collected. It also reviews the results of the buried T1 system assessment and summarizes the relevant data. Based on these data, conclusions are drawn concerning the survivability of typical aerial T1 cable systems. Finally, recommendations are presented for addressing remaining issues relevant to this assessment.

To avoid the added time and expense of conducting an operational test program, the testing portion of this effort was conducted as a coupling and propagation study for representative T1 aerial cable configurations. The results of the coupling study are used in conjunction with the results of related test programs (References 1 and 2) to assess the survivability of typical lightning protected and unprotected T1 systems against early-time HEMP. The measured cable transients and cable properties are used to establish the threat signal levels that could be seen by aerial T1 system repeaters, channel banks, and Transient Protection Devices (TPDs). Repeaters and TPDs were tested during the Buried T1 Carrier tests; the unhardened D4 channel bank was tested in a separate program (Reference 2).

The HEMP threat environment considered for the purposes of this report is the early-time, unclassified 50 kV/m peak amplitude double exponential (DBEX) discussed in Reference 3. The early-time, classified environment (E1 of DOD-STD-2169) and estimated transient responses are discussed in the classified appendix to this report. The mid- and late-time environments (E2 and E3) have been addressed in previous reports (References 1 and 3). Volume 6 of Reference 1 discusses the estimated transient response of the buried T1 cable to E2 and E3. Reference 3 compares the estimated transient responses of both aerial and buried T1 cables to the DBEX and E1 threats.

Testing was performed at Harry Diamond Laboratories at Woodbridge, VA to assess the HEMP coupling onto the aerial T1 configuration. Since no specifications and test data are readily available for the KHAG 106 cable, the first step was to quantify its physical and electrical characteristics. The overall cable construction was examined, measuring such parameters as diameter, aluminum shield thickness and DC resistance per unit length, and propagation velocity factors. The same tests were then performed with a splice case installed in the cable to determine how these characteristics are affected.

The results of this analysis show that the survivability of the D4 Channel Bank equipment is highly dependent on the placement of the splice cases. T1 equipment near a splice case (< 10 m) may see surges of over 100 A. T1 line repeater and Central Office equipment should survive exposure to such transients, but the D4 channel bank appears to be vulnerable to HEMP effects at the Alarm, VF, T-carrier, and Power interfaces. For example, if a splice case is placed 200 m from the equipment, the induced current on the equipment will be about 4 A. In this configuration only the D4 VF Interface will fail. However, if a splice is placed 25 m from the equipment, then the induced current on the equipment will be about 40 A. In this case, the D4 VF, T-carrier and Power Interfaces will fail.

EXHIBIT ES-1
Failure Thresholds for T1 Line Equipment

Component	Failure Current (A)	Risetime (ns)
Line Repeater	300-400	10-50
CO Repeater	300-400	10-50
D4: Alarm	90	~ 70
VF	3	~ 70
T-carrier	13-27	75-85
Power	37	~ 55

Various issues remain unresolved that could have an impact on the survivability of aerial T1 carrier installations. These issues include:

- The number and placement of splice cases between repeaters or central office equipment. This analysis assumed no synergistic effects, which could limit the applicability of these results.

- The effects of a non-ideal grounding system. The test data were collected using the most ideal ground connections achievable for the test setup. This assessment should be expanded to include appropriate inductances and resistances of real world ground systems.

1.0 INTRODUCTION

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The Office of the Manager, National Communications System (OMNCS) has undertaken the Electromagnetic Pulse (EMP) Mitigation program to support the survivability objectives addressed by National Security Decision Directive 97 (NSDD-97) and Executive Order 12472. The objective of this program is to mitigate the damaging effects of nuclear weapons on regional and national telecommunications capabilities. To meet this objective, the OMNCS has sponsored efforts to create a network-level model to assess the effects of high-altitude EMP (HEMP). In addition, the OMNCS has sponsored various efforts to collect the system-level HEMP effects data required to support the network-level model. The products of this model assist the OMNCS in identifying potential vulnerabilities of national telecommunications capabilities to HEMP and supporting National Security and Emergency Preparedness (NSEP) initiatives.

1.1 PURPOSE

In support of the OMNCS efforts to assess the network-level survivability of NETS, the OMNCS is sponsoring efforts to assess the equipment-level effects of HEMP on aerial T1 carrier equipment. The survivability of buried T1 systems against the effects of HEMP was the subject of extensive analysis and testing efforts under the T1/FT3C Nuclear Weapons Effects project, which was funded by the OMNCS (Reference 1). As a result of these efforts, a wealth of information exists, some of which is applicable to the aerial T1 equipment. The approach to the aerial T1 assessmen is to use as much of the existing data as possible and to augment that data, where appropriate, through analysis and simulation testing in order to identify potential vulnerabilites to HEMP.

This report presents an assessment of the survivability of aerial T1 systems in a HEMP environment. This effort includes a test program to collect the data required to assess coupling of incident electromagnetic fields to aerial T1 cables. This report documents the test activities and the data collected. It also reviews the results of the buried T1 system assessment and summarizes the relevant data. Based on these data, conclusions are drawn concerning the survivability of typical aerial T1 cable systems. Finally, recommendations are presented for addressing remaining issues relevant to this assessment.

1.2 SCOPE

To avoid the added time and expense of conducting an operational test program, the testing portion of this effort was conducted as a coupling and propagation study for representative T1 aerial cable configurations. The results of the coupling study are used in conjunction with the results of related test programs (References 1 and 2) to assess the survivability of typical lightning protected and unprotected T1 systems against early-time HEMP. The measured cable transients and cable properties are used to establish the threat signal levels that could be seen by aerial T1 system repeaters, channel banks, and Transient Protection Devices (TPDs). Repeaters and TPDs were tested

during the Buried T1 Carrier tests (Reference 1); the unhardened D4 channel bank was tested in a separate program (Reference 2).

Many equipment vendors exist for T1 carrier transmission systems. For the purpose of this program, the hardware and installation procedures used in this assessment are representative of those found in current aerial installations.

The HEMP threat environment considered for the purposes of this report is the early-time, unclassified 50 kV/m peak amplitude double exponential (DBEX) discussed in Reference 3. The early-time, classified environment (E1 of DOD-STD-2169) and estimated transient responses are discussed in the classified appendix to this report. The mid-and late-time environments (E2 and E3) have been addressed in previous reports (References 1 and 3). Volume 6 of Reference 1 discusses the estimated transient response of the buried T1 cable to E2 and E3. Reference 3 compares the estimated transient responses of both aerial and buried T1 cables to the DBEX, E1, and E2 threats.

1.3 OBJECTIVES

The purpose of this report is to develop an empirical data base describing the characteristics of transients induced on typical aerial T1 cables in the EMP threat environment, and to assess system survivability in a threat environment using this data. To achieve this goal, this report will describe the test, summarize the test results, and estimate the expected threat waveforms. The report will then summarize relevant buried T1 data and determine the damage thresholds of individual components. Using this data, the report will then assess system survivability and identify areas requiring further testing.

1.4 ORGANIZATION

- Chapter 2.0 provides an overview of typical aerial T1 equipment and installation procedures. The actual equipment used in the test, and the reasons for using it, are also described.

- Chapter 3.0 describes the test setup and gives a summary of the data collected.

- Chapter 4.0 presents an analysis of the data. A translation of data into model parameters and a prediction of transients is also given.

- Chapter 5.0 presents the thresholds of all T1 carrier equipment as determined in the buried T1 and D4 channel bank studies.

- Conclusions and Recommendations are presented in Chapter 6.0. An assessment of the survivability of the aerial T1 system is made by comparing the threat determined in Chapter 4.0 with the thresholds determined in Chapter 5.0.

- The survivability of T1 system components to the DOD-STD-2169 threat is presented in Volume II of this report.

2.0 T1 DIGITAL CARRIER

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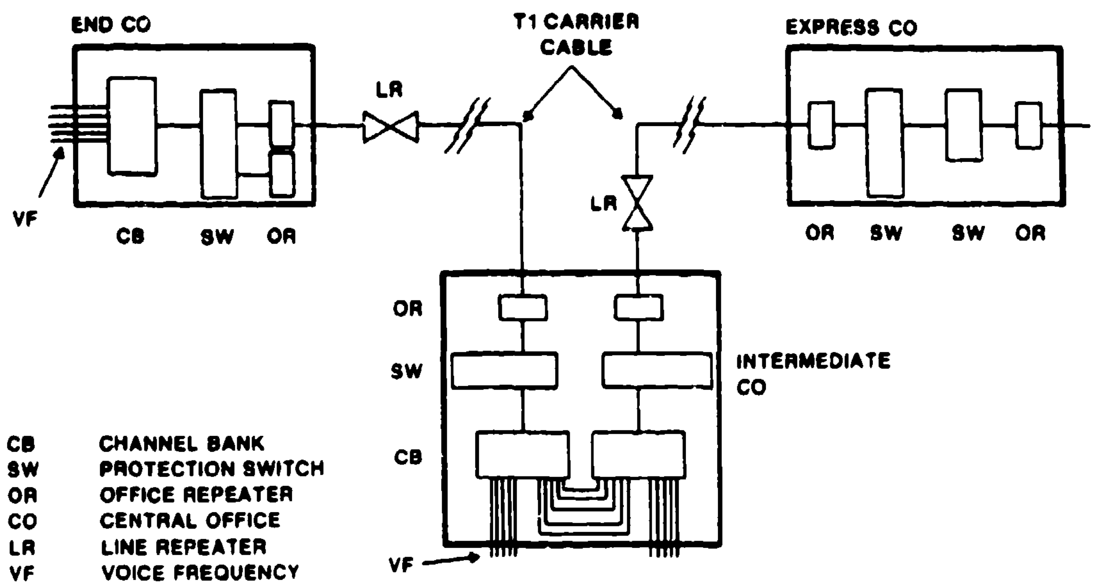
T1 digital carrier was the initial short-haul digital transmission line used within the Bell System. The transmission media for T1 can be pulp, air-core PIC, or jelly-filled PIC cables from 16 to 26 gauge. The signal is transmitted in a 1.544-megabit-per-second pulse stream, which can be generated from a variety of terminals, such as the D4 channel bank discussed later in this section. This signal is applied directly to cable pairs in a bipolar format.

2.1 T1 CARRIER HARDWARE

A typical T1 carrier system might be arranged as shown in Exhibit 2-1. The Central Office (CO) equipment is shown in the boxes and is interconnected by the outside plant equipment, consisting of T1 carrier lines. The remote customer end is served by the channel bank, protection switch, and office repeater combination as shown on the left. The optional protection switch changes to a spare T1 carrier line in the event of a signal failure at the receiving end. At an intermediate CO (e.g., in the lower box) the entire 24-voice-channel group (digroup) is demultiplexed so that some voice-frequency (VF) channels may be directed to a customer while the remaining VF channels are to be multiplexed onto the outgoing T1 carrier. The third type of office configuration shown in Exhibit 2-1 (upper right) is used for supplying power to the T1 carrier line; there is no VF application.

EXHIBIT 2-1
Typical T1 Carrier System Configuration



The outside plant equipments for this system are repeaters and splice cases. Regenerative repeaters in the central office and on the line retime and regenerate transmitted bipolar signals. Repeaters are solid-state plug-in units suitable for pole mounting or manhole placement. The transmitted digital signal travels on twisted pairs, balanced to ground, which have a nominal source impedance of 100 ohms. Spacing of T1 repeaters ranges from one mile to 6,000 feet. Typical pole-mounted and manhole repeater installations are shown in Exhibit 2-2(a) and (b). The dc power for repeater equipment is supplied over the digital transmission line. Line repeaters are powered in a series loop containing up to 17 repeaters.

The typical repeater unit tested during the buried T1 carrier study was an 800-type plastic case housing two 239 E/F 60 Hz protected repeaters with standard lightning protection devices (208A gas tubes) installed. The 818/819-type repeater case is designed to house 25 T1 carrier repeaters, a fault locate filter, a pressure contactor, and other ancillary equipment. The case is molded from a fiberglass-reinforced plastic (sheet molding compound) and is designed to be either pole-mounted (for aerial T1 systems) or installed in a manhole (for buried T1 systems).

The cast-iron splice case shown in Exhibit 2-3 is designed to be used aerially, buried, or in manholes. Cable-sheath continuity at the splice case is achieved through the cast-iron halves of the splice case itself and with a copper braid.

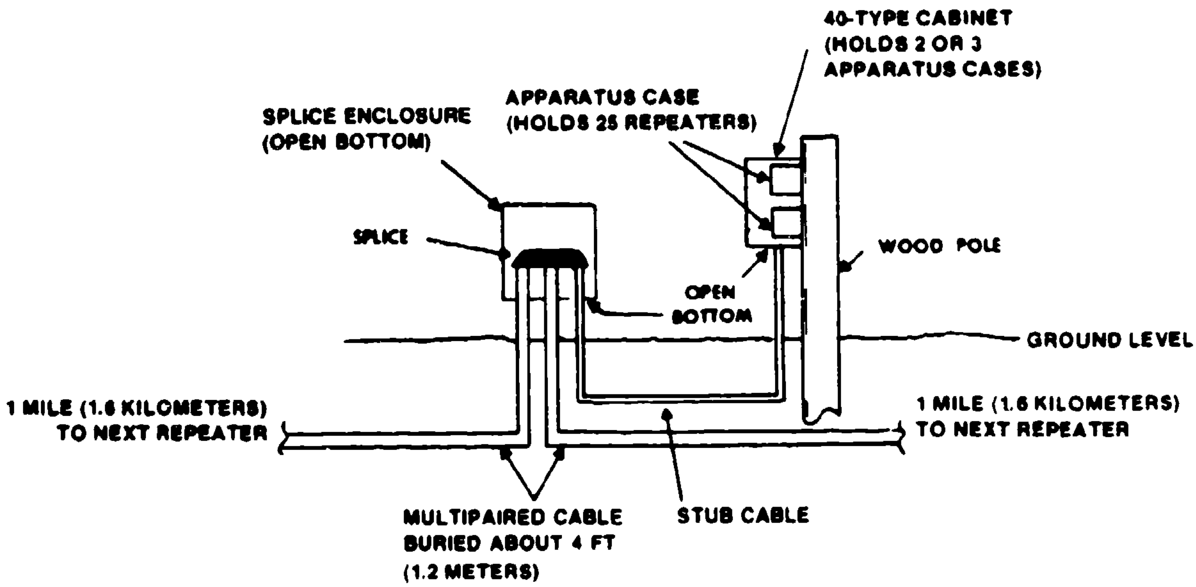
The plastic splice case shown in Exhibit 2-4 is also designed to be used aerially, buried, or in manholes. Cable-sheath continuity is achieved by bridging across the splice with a copper braid. This arrangement provides a current path across the splice.

The pedestal-type closure shown in Exhibit 2-5 is designed for use with buried or aerial cable where the splice closure can be mounted at ground level. Continuity of the cable sheath at the splice is achieved with copper bonding cables that provide a DC path across the splice.

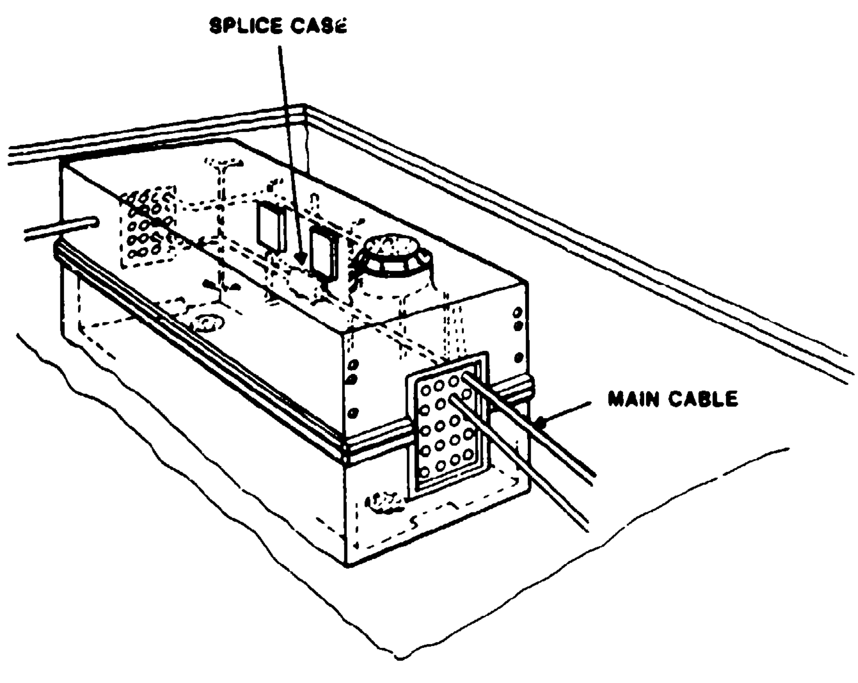
Because plastic splice cases offer less shielding than either cast-iron or pedestal-type splice cases, their use allows significantly more severe transients to couple directly to the internal signal carrying conductors than would the other two splice cases. The results of the cable drive study incorporating plastic splice cases will therefore determine a reasonable upper limit on the transients expected on T1 cables incorporating either cast-iron or pedestal-type splice cases. The typical splice case tested during the buried T1 carrier study was a PC-12 mounted above ground.

For all T1 central office equipment, conventional mounting is in open bays (equipment racks). An important piece of office equipment is the channel bank (most commonly D4), which provides the voice-frequency interface to the digital (T1) line. In T1 systems not requiring an interface to analog voice channels, the channel bank is not used. The channel bank samples the analog voice-frequency signal, converts it to a PCM bit stream, and assembles the digitally-encoded voice frequency

EXHIBIT 2-2
Typical T1 Repeater Installations



(a) Pole-mounted Repeater



(b) Manhole-Installed Repeater

EXHIBIT 2-3
Cast-Iron Splice Case

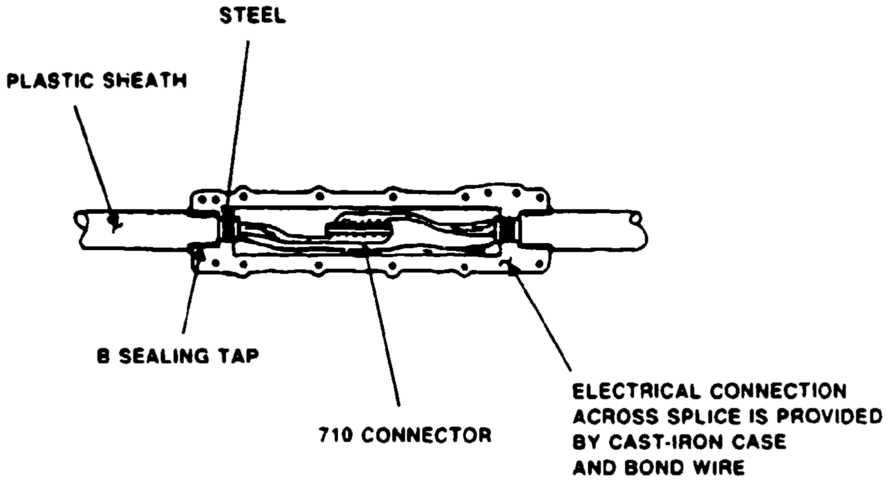


EXHIBIT 2-4
Plastic Splice Case (2 type)

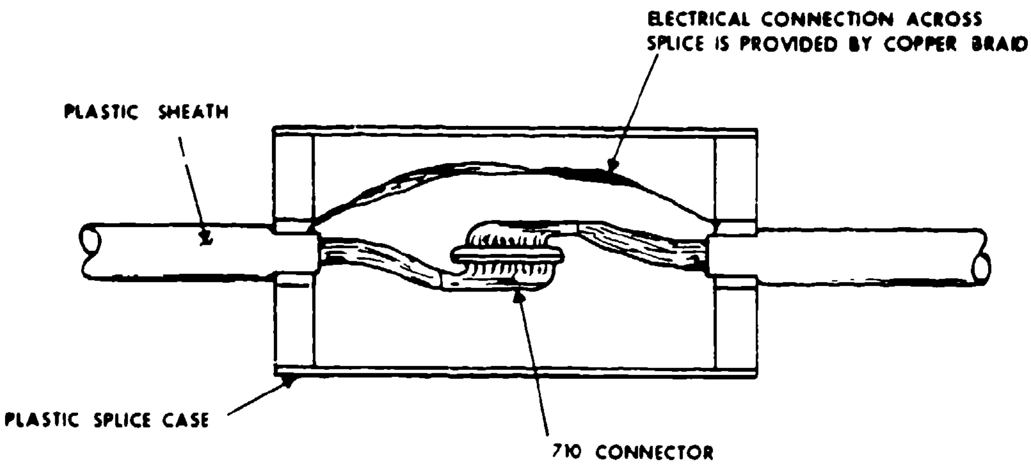
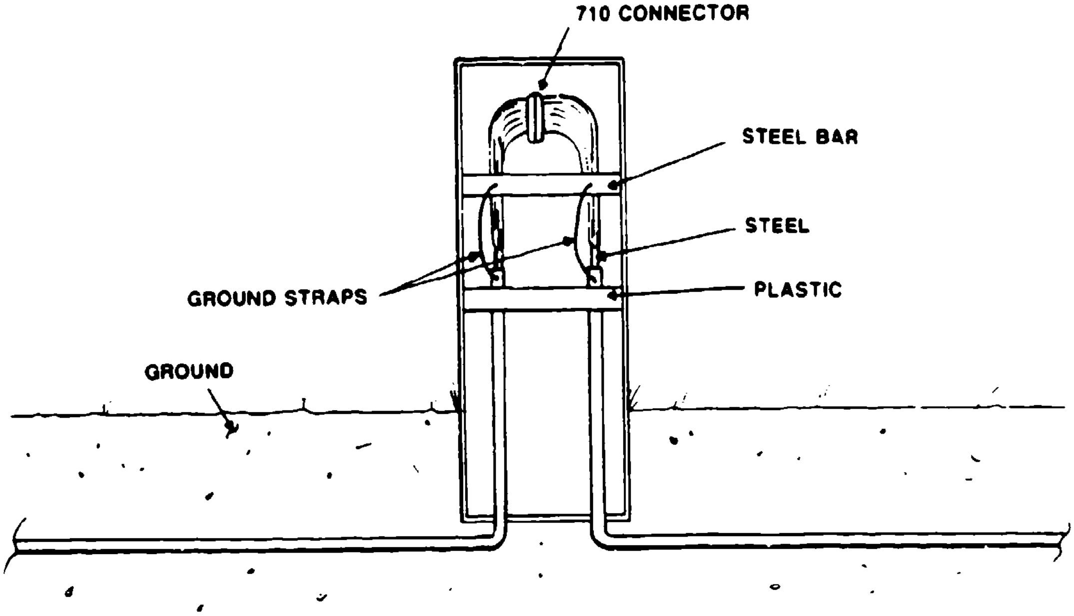


EXHIBIT 2-5
PC-12 Cable Enclosure



signals from 24 voice channels and framing information into the 1.544 Mbits/s line signal. In the other transmission direction, the channel bank provides the inverse functions.

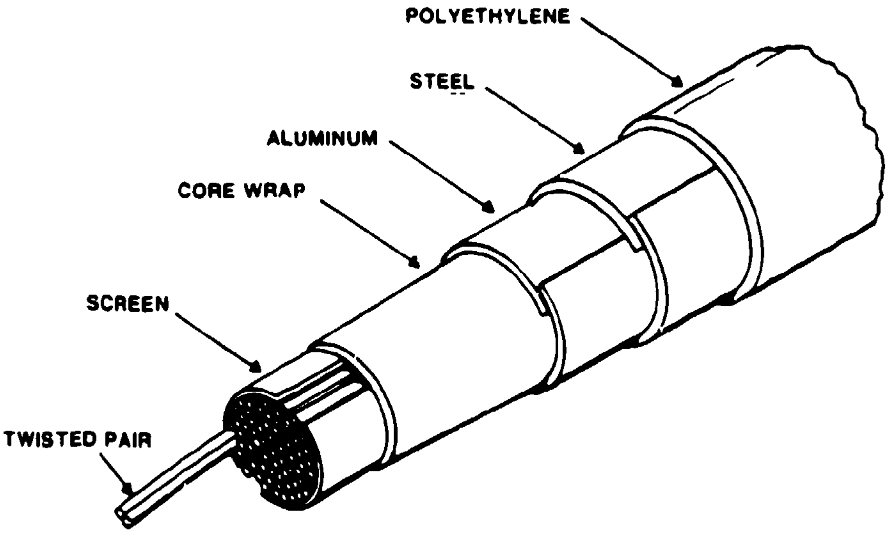
A channel bank physically consists of shelves in an equipment frame filled with printed circuit boards. There are two basic types of circuit boards in the bank: channel units, devoted to functions involving individual voice channels; and common units, devoted to functions involving the digital line or entire bank. The voice-frequency pairs terminated at a channel unit are balanced to ground and may serve as either two-wire or four-wire circuits. Signaling is accomplished by various dc arrangements over the voice-frequency leads, or by separate signaling pairs. As a result, a single two-way voice-frequency circuit may have as many as eight pairs of leads at the channel bank interface. The common equipment boards supply maintenance and alarm functions, multiplexing functions, line and office interface functions, and certain other functions such as trunk processing and timing. Common equipment also includes high-frequency circuits, which provide the digital line interface.

2.2 TEST SAMPLE DESCRIPTION

The cable used for this test was KHAG 106 (Aerial T1) cable. It is typical of the aerial T1 cables used to interconnect telephone central offices throughout the United States.

Exhibit 2-6 illustrates the structure of the KHAG 106. This cable was chosen because its configuration (size, number of twisted pairs, number and type of shields) is typical of cables used for T1 transmission within the PSN. The cable has 106 color-coded twisted pairs of #22 AWG wire arranged in groups of 25 pairs called binder groups. The remaining six wire pairs are called maintenance pairs and are used as alternate carrier pairs if one of the other main carriers becomes disabled. Each binder group as well as the individual wire pairs twists at a uniform rate with respect to the others, but they do not braid. The KHAG 106 has four binder groups; two binder groups are used to transmit the digital T1 signals, and the other two binder groups are used to receive the signals. The two pairs of binder groups are shielded by a 0.2 mm thick aluminum screen. Although this screen is not used in all T1 cables, it is incorporated in the KHAG 106 to prevent cross-talk between the binder groups. An inner polyethlyene jacket surrounds the binder groups and aluminum screen, while the core of the cable is shielded primarily by a corrugated aluminum sheath with a continuous overlapping lateral seam. The outer jacket is comprised of a weatherproof PVC material. The nominal outside diameter of the cable is 34.3 mm (1.35 inches).

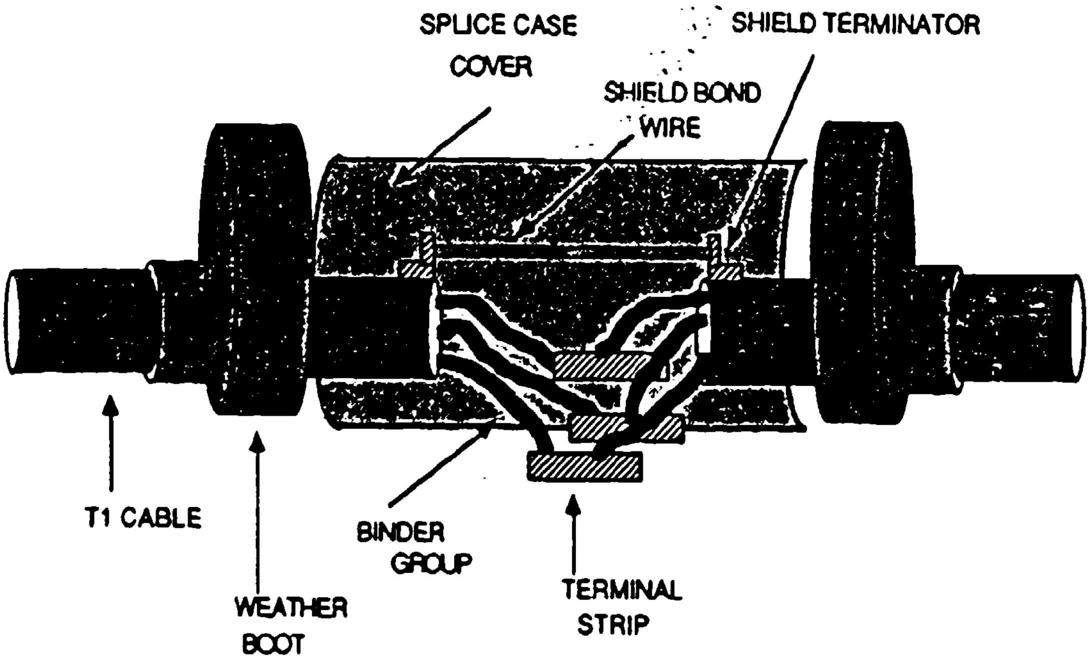
EXHIBIT 2-6
Structure of KHAG 106 Aerial T1 Cable



The first sample is 102 ft. of KHAG 106. The second cable sample used is identical to the first, except that it has a splice case installed 10 ft. from one end of the cable. The splice was performed in accordance with the current design and installation practices used in the telecommunications industry.

The splice case tested during the aerial T1 carrier study was the fiberglass-reinforced plastic 50B3-type splice closure, as shown in Exhibit 2-7. The case of the 50B3 is comprised of a PVC material with two rubber weather boots at each end. Each binder group is terminated into a terminal strip where it is mated with a matching strip from the incoming/outgoing cable; the maintenance pairs are mated in the same fashion. The aluminum shields of the two sections of cable are tied together using a length of #6 AWG copper wire, which is attached using a shield termination device.

EXHIBIT 2-7
Cut-away View of the Aerial T1 Splice Case



3.0 TEST RESULTS

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Several types of tests were performed in the laboratory to accurately determine the coupling characteristics of the aerial T1-type cable (KHAG 106) to simulated-EMP transients. This section presents the results of the laboratory cable driving studies. These tests were designed to provide the test data required to support analysis of HEMP-induced transients on aerial T1 cables. These analyses are presented in section 4.0.

When compared to the EMP frequency spectra (10 kHz to 100 MHz), typical lengths (> 100 ft.) of T1 cable are electrically long; thus, several complex coupling mechanisms are significant. The coupling theory is complex and mathematical analysis is extremely difficult; therefore, the best approach for determining the coupling to the cable is based on physical and electrical tests.

Since no specifications and test data are readily available for the KHAG 106 cable, the first step was to quantify its physical and electrical characteristics. The overall cable construction was examined, measuring such parameters as diameter, aluminum sheath thickness, DC resistance per unit length, and propagation velocity factors. The same electrical tests were then performed with a splice case installed in the cable to determine how these characteristics are affected. These results are summarized in this section.

To properly assess the amount of EMP energy coupling onto a signal wire inside a shielded cable, several laboratory tests must be performed on the cable sample to determine certain cable parameters including characteristic impedance, insertion loss, and transfer impedance. Assuming that no data exist on the cable being tested, the TDR test must first be conducted to determine the characteristic impedance of the cable. This information is important, so that the impedances of the cable signal wires and the sheath can be matched to eliminate standing waves and resonances during subsequent testing.

Insertion loss testing, which is performed using a network analyzer, determines cable attenuation over a wide frequency range. Since EMP is a broadband frequency phenomenon spanning several decades, it is important to know what spectrum of the EMP threat, if any, will be attenuated by the cable as the signal propagates down the signal wire to the load.

Transfer impedance testing measures the coupling of signals from the cable sheath to the inner signal conductors. During testing, the cable sheath is driven with a current and the induced voltages on the loads attached to the signal wires are measured. The sheath current is swept in frequency to cover the wide range of the EMP spectrum; the low- and high-frequency characteristics of the cable sheath coupling to the signal wires can then be determined. Based on the transfer impedance data, the voltages coupled on the loads can be mathematically predicted for higher threat-level sheath currents.

The pulse test data are used to verify the transfer impedance data. By driving the cable sheath with a current pulse of a specific risetime and pulse width, the coupled voltages on the load resistors attached to the signal wire can be measured. The magnitude of the coupled pulse should agree with the convolution of the pulse driven on the shield with the transfer impedance data taken previously. If both are in agreement, then the cable has been accurately characterized, and one can use the test data to mathematically predict the coupled quantities for a higher sheath current.

3.1 TIME-DOMAIN REFLECTOMETRY (TDR) EXPERIMENTS

Since little was known about the electrical properties of the cable, the first series of tests used TDR. By injecting a known pulse on an inner conductor and measuring the pulse reflection propagating back to the source, the propagation velocity and characteristic impedance (Z_o) of the cable were determined.

TDR tests were performed on two samples of KHAG-106 cable. Sample 1 is 102 ft of cable and sample 2 is 102 ft of cable with a splice case installed. See section 2.2 for test sample descriptions.

The TDR tests were performed using a Tektronix 7S12 TDR/General Purpose Sampler. The system used the S-6 sampling head and the S-52 pulse generator head. The TDR sends a fast rise time (45 ps) pulse with an amplitude of several volts down the test sample and measures the reflected wave, which is displayed on the CRT display of the TDR's oscilloscope. By analyzing this reflected wave, the characteristic impedance, propagation time, and any cable discontinuities can be measured.

3.1.1 CHARACTERISTIC IMPEDANCE

The TDR tests were first performed on the cable with no splice case (sample 1). Both the individual wire to wire impedances and wire to sheath twisted-pair impedances were measured. Exhibit 3-1 is a tabulation of the results. The wire/wire impedance is defined simply as the impedance measured across a given twisted-pair of wires. The wire/sheath impedance is likewise defined as the impedance measured from a given wire to the cable sheath; this impedance is the same when measured from either wire within the denoted twisted-pair. When all twisted pairs are tied together, the wire/sheath impedance is significantly less than when the wire/sheath impedance is measured from individual wires within a given binder group. Since the cable contains over 200 conductors, a representative sample of conductors in each binder group was measured. Exhibit 3-2 displays sample photos of reflected TDR pulses (Appendix A contains all the raw data). The test configuration is shown in Exhibit 3-3.

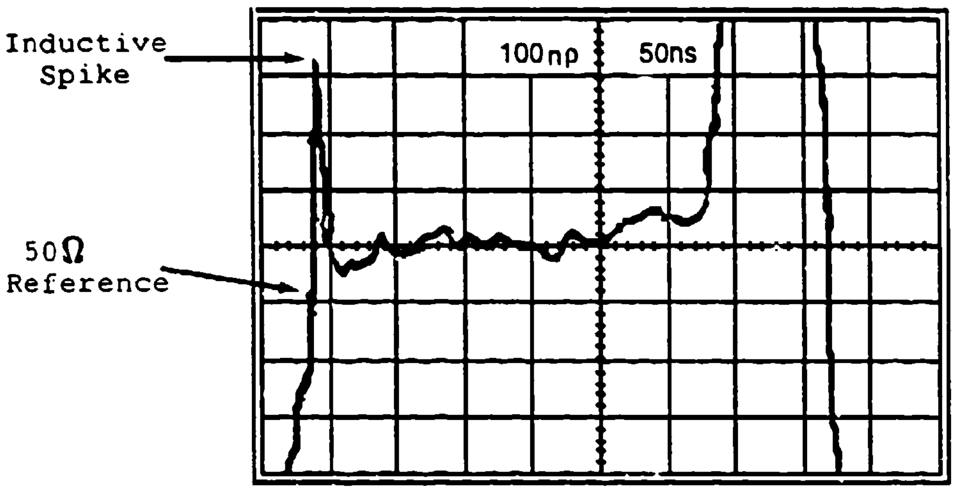
The inductive spike seen at the beginning of the pulse as shown in Exhibit 3-2 is due to the inductive and mismatched connection between the TDR and the test sample. The level then settles down to the characteristic impedance of the cable, which can be calculated from the data tabulated in Exhibit 3-1. One notices that the impedance varies over

EXHIBIT 3-1
Wire/Wire and Wire/Sheath Impedances
for Cable with No Splice Case (Sample 1)

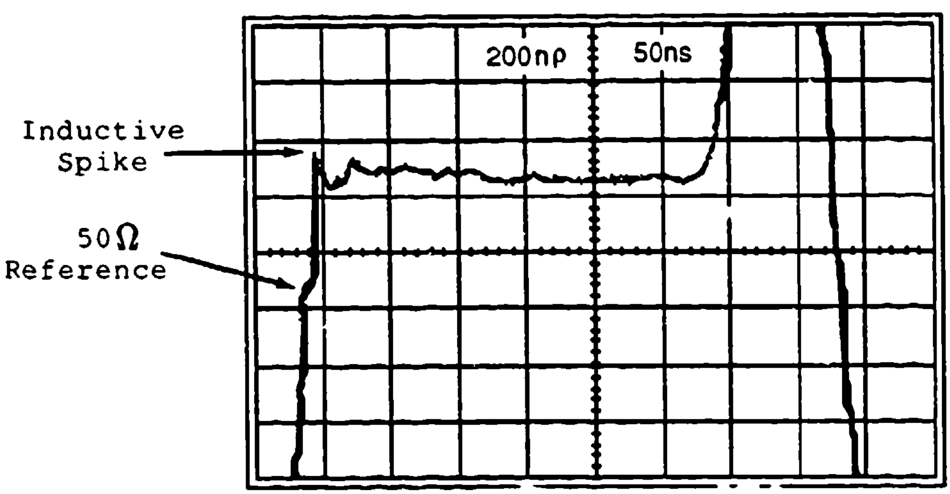
Binder Group	Pair	Wire/wire Impedance (Ω)	Wire/sheath Impedance (Ω)
All†	All‡		16
Blue	All		21
Green	All		21
Brown	All		21
Orange	All		21
Red	All		33
Maint	G/W	93	75-92*
Maint	BL/W	93	75-92
Maint	GY/W	93	75-92
Brown	O/V	93	78
Brown	O/W	120	78
Brown	O/R	120	78
Brown	O/Y	120	72
Brown	G/B	120	78
Brown	BR/B	120	78
Brown	GY/V	120	78
Brown	BL/W	120	111
Blue	O/R	112	72
Blue	O/V	93	72
Blue	O/W	112	72
Blue	O/Y	93	72
Blue	BL/W	112	70-72
Blue	G/B	112	72
Blue	BR/B	112	72
Blue	GY/V	112	72
Green	O/R	117	72
Green	O/V	117	72
Green	O/W	117	72
Green	O/Y	88	72
Green	BL/W	88	88
Green	G/B	117	85
Green	BR/B	117	72
Green	GY/V	117	72
Orange	O/R	100	75
Orange	O/V	100	75
Orange	O/W	100	75
Orange	O/Y	100	75
Orange	BL/W	116	75
Orange	BR/B	116	75
Orange	GY/V	116	75

† All binder groups were connected for this measurement
‡ All wire pairs were connected for this measurement
* The current varied over this range.

EXHIBIT 3-2
Sample Photos of Reflected TDR Pulses
for Cable with No Splice Case (Sample 1)

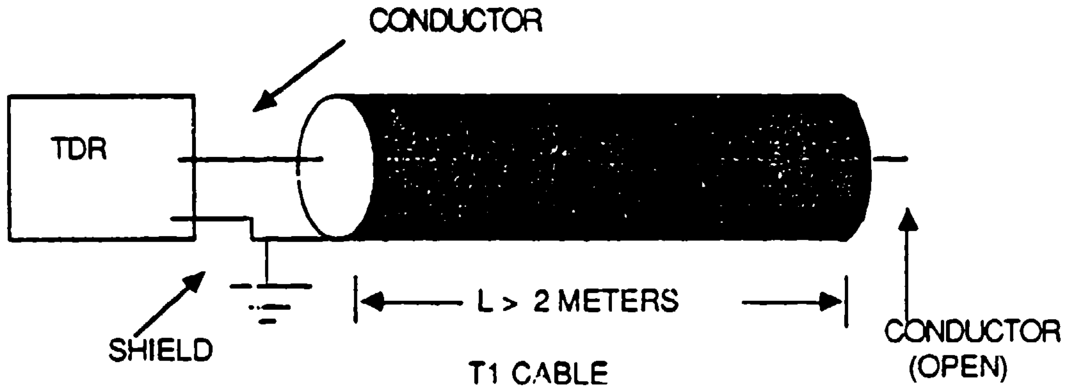


(a) Wire to Sheath Impedance



(b) Wire to Wire Impedance

EXHIBIT 3-3
TDR Test Configuration



the length of the cable; this is a result of the cable construction. The spacing between the wires/binder groups, with respect to the outer sheath, do not remain constant with length. Slight twists in the wire bundles, therefore, change the physical dimensions between the conductors and the sheath, thus changing the characteristic impedance.

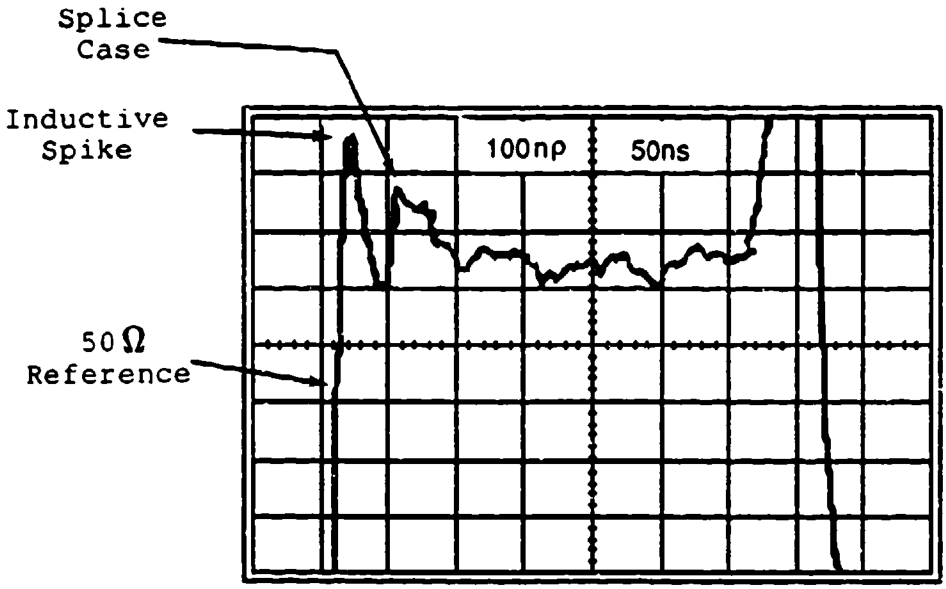
The second sample to be tested was the cable with the splice case (sample 2). The primary objective of this testing was to quantify the impedance mismatch between the splice case and the aerial T1 cable. The same wires/bundles and pairs that were measured during the test of the first sample were tested here to facilitate a direct comparison between the two samples. The test data for sample 2 are tabulated in Exhibit 3-4. Because the splice case has a different characteristic impedance than the cable itself, the wire/wire and wire/sheath impedances were measured both at the cable end and within the splice case. The wire/sheath impedance is the same when measured from either wire within the denoted twisted-pair, except where noted by a "/;" in this case, the first number represents the impedance from the first wire within the noted pair, and the second number represents the impedance from the second wire within the noted pair. Exhibit 3-5 displays sample photos of reflected TDR pulses for sample 2.

The discontinuity introduced by the splice case is significant, as shown by the photos of Exhibit 3-5. When compared to the characteristic impedance of the cable itself, the splice case mismatch causes significant reflections of transients propagating on the internal cable wire pairs, which result in an effective pulse width much larger than the incident pulse. The lengthened pulse width may be significant in the assessment of the survivability of sensitive electronic circuitry connected to an internal cable wire.

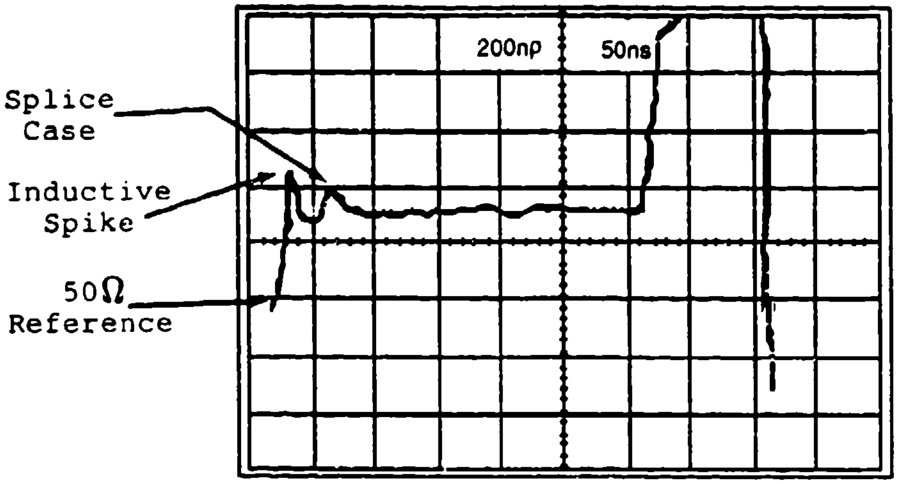
EXHIBIT 3-4
Wire/Wire and Wire/Sheath Impedances for Cable with Splice Case (Sample 2), Measured at Cable End and at Splice Case

Binder Group	Pair	Wire/wire Impedance (Ω)		Wire/sheath Impedance (Ω)	
		at Cable End	at Splice Case	at Cable End	at Splice Case
All	All			16	22
Blue	All			26	75
Green	All			26	75
Brown	All			26	75
Orange	All			26	75
Red	All			40	43
Maint	G/W	104	118	88	120
Maint	BL/W	104	118	83	111
Maint	R/BL	104	118	80	122
Maint	BR/W	104	118	83-92	107
Maint	GY/W	104	118	80-105	120
Brown	O/R	105	118	81	109
Brown	O/V	109	118	81	109
Brown	O/W	105	118	85	109
Brown	O/Y	105	118	85	109
Brown	BL/W	105	118	85	109
Brown	G/B	105	118	78	101
Brown	BR/B	109	120	78	101
Brown	GY/V	109	120	78	109
Blue	O/R	109	116	85	116
Blue	O/V	116	121	85	116
Blue	O/W	109	116	88	116
Blue	O/Y	109	116	88	116
Blue	BL/W	109	111	88	116
Blue	G/B	109	116	78	116
Blue	BR/B	109	116	78	116
Blue	GY/V	109	116	78	109
reen	O/R	109	112	77	110
Green	O/V	109	112	79	108
Green	O/W	120	128	83	111
Green	O/Y	109	112	83	111
Green	BL/W	109	112	88	115
Green	G/B	109	112	83	103
Green	BR/B	109	112	83	103
Green	GY/V	109	112	83	103
Orange	O/R	92	110	83	115
Orange	O/V	122	135	92/83	115
Orange	O/W	122	135	83/106	112
Orange	O/Y	92	110	92	115
Orange	BL/W	92	110	92	115
Orange	GR/B	111	122	83	106
Orange	BR/B	111	122	78/89	110
Orange	GY/V	92	110	83	106

EXHIBIT 3-5
Sample Photos of Reflected TDR Pulses
for Cable with Splice Case (Sample 2)



(a) Wire to Sheath Impedance



(b) Wire to Wire Impedance

Since the plastic splice case offers no electromagnetic shielding, the interior wire pairs are subjected to the full external field resulting from the EMP. The internal wires act as small dipole antennas coupling the full free-field EMP threat onto the conductors. This coupling mechanism is addressed in the cable drive tests (see section 3.3). The data obtained in the TDR tests aids in matching the internal wire and cable impedances during the cable drive tests. This minimizes reflections and ringing during tests where the cable is driven with a high-current pulse.

3.1.2 PROPAGATION VELOCITY

The propagation velocity of both samples can be determined from the TDR data. The roundtrip time of the TDR pulse is roughly 275 ns, as can be seen from the TDR data in Appendix A. Given a cable length of 102 ft, the propagation time for a pulse on the T1 cable is found to be 4.42 ns/m. See section 4.1 for a derivation of this result.

3.2 DC SHEATH RESISTANCE MEASUREMENTS

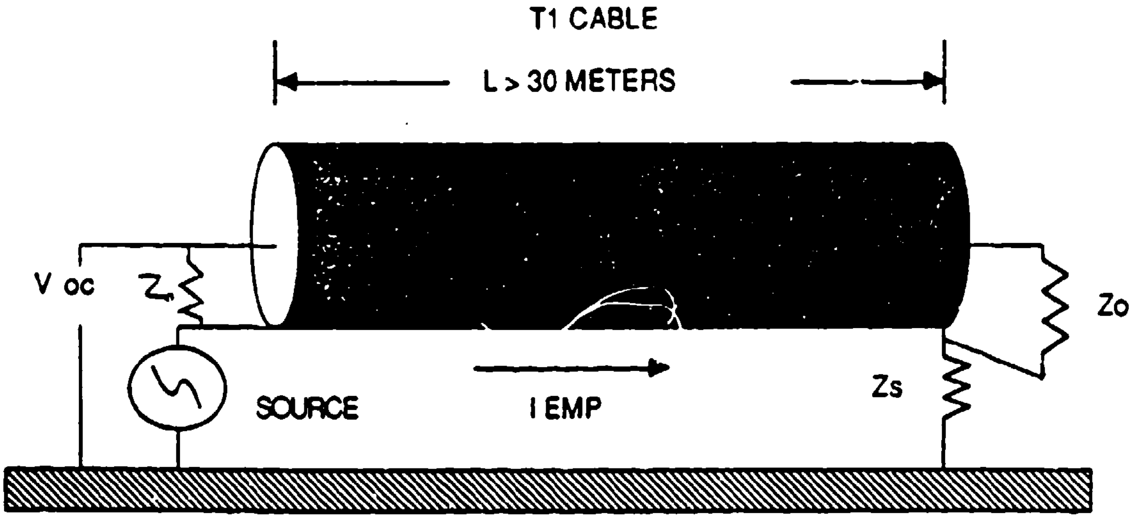
To estimate the shielding performance of an electrically short cable, the DC resistance of the KHAG 106 cable sheath was measured. Bond straps and splice cases were then integrated into the cable as they would be in a typical aerial T1 installation. The DC resistance of the cable sheath was again measured to determine how the addition of the bond straps and splice cases affected DC measurements. The DC resistance of the 102 ft cable (both with and without a splice case) is 0.050 Ω. This corresponds to a DC resistance of 1.7 mΩ/m. The thickness of the sheath was measured to be 2.03×10^{-4} m. The maximum shielding effectiveness for electrically short cables can be approximated from this DC data; the DC resistance approximates the low-frequency transfer impedance (Z_t).

3.3 DIRECT DRIVE MEASUREMENTS

Direct-drive cable testing was conducted to characterize coupling of large transients on the cable sheath to the signal-carrying conductors within the cable. For the purposes of this test, an electrically long (ℓ = 30 m) piece of T1 cable was strung above a ground plane. At one end of the cable, the inner conductors were terminated into their characteristic impedances (determined through the TDR experiments) to ground. At the same end, the sheath was tied directly to ground. At the other end of the cable, the sheath was tied to a current drive source through a 56.6 Ω resistor (see Exhibit 3-6). The currents through the termination resistors were measured to determine the open circuit voltage (V_{oc}).

Splice boxes and ground straps were then installed near the end of the cable to simulate a real world situation. The sheath was again tied to a current drive source, and the open circuit voltages and short circuit currents were measured to show the effect of these fixtures on the overall performance of the cable sheath. The peak coupled current during testing was 23 A. The current injected onto the sheath was a decaying exponential pulse with a peak amplitude of 1.6 kA. The

EXHIBIT 3-6
Test Setup for Long Line Pulsing



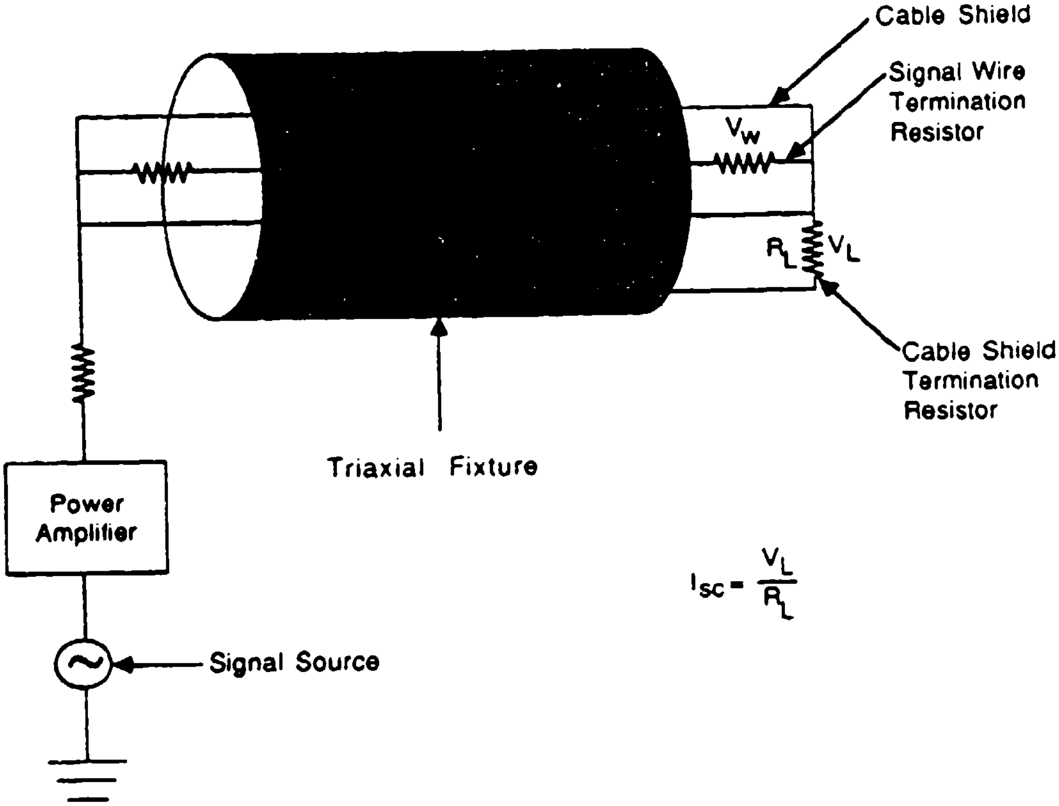
current pulse had a rise time of between 150 ns and 200 ns and a decay time of about 2.5 μs. The measured current transients coupled to the signal wires in the cable without a splice case measured approximately 600 mA. The pulse shape resembles that of the incident pulse with a slight time shift due to diffusion. The measured current transients coupled to the signal wires in the cable with a splice case rang at roughly 2.5 MHz and had a peak to peak amplitude of between 10 A and 23 A. A more complete analysis of the results (including photographs of typical current pulses) is given in section 4.

3.4 TRANSFER IMPEDANCE EXPERIMENTS

The transfer impedances of two 2-meter samples of Aerial T1 cable (one with a splice case and one without a splice case) were measured using a triaxial transfer impedance test fixture, which drives a reference signal onto the cable sheath. The cable sheath is terminated to the fixture by a resistor (R_t) whose value matches the characteristic impedance formed between the cable sheath and the triaxial fixture. The basic test setup is depicted in Exhibit 3-7. This configuration drives a current (I_{sh}) on the cable sheath. I_{sh} is determined by measuring the voltage (V_{sh}) across the load resistor (R_t). The sheath current can be calculated using the following formula:

$$I_{sh} = V_{sh}/R_t$$

EXHIBIT 3-7
Transfer Impedance Test Configuration



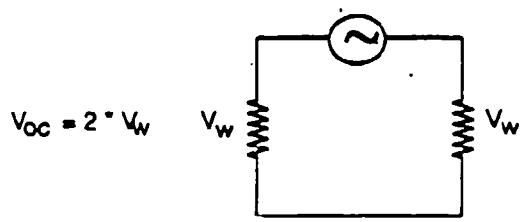
The signal wire of inte st is terminated at both ends to the cable sheath by a resistor (whose value matches the characteristic impedance of the wire-to-cable-sheath), forming a voltage divider on the signal wire between the two termination resistors. Since the resistors are of equal value (R_w), the voltage developed across one of the resistors is half of the total open circuit or driving voltage (V_{oc}). Therefore, the voltage across one of the termination resistors is measured and multiplied by two to give V_{oc}. Exhibit 3-8 shows an equivalent circuit diagram of the circuit developed.

The transfer impedance (Z_t) can be readily calculated using the following formula:

$$Z_t = V_{oc}/I_{sh}$$

The most accurate method of determining the transfer impedance is to use a programmable network analyzer, which measures the voltages of interest and mathematically calculates the transfer impedance (Z_t) across a broad spectrum of frequencies. The analysis described in this section was conducted with such a network analyzer.

EXHIBIT 3-8
Equivalent Circuit Diagram
for Triaxial Test Fixture



Equivalent Circuit

The non-splice case, low- frequency data corresponds with the measured DC value of 3.8 mΩ for a 2.4 meter section of cable. Correspondence between the DC value and the measured data verifies that the test data is accurate. Since the test equipment had frequency limitations above 6 MHz, no test data could be gathered for high frequencies. The high frequency response of the cable was therefore estimated through mathematical analysis. The transfer impedance of a braided cable with uniformly distributed imperfections can be calculated using the following formula (Reference 4):

$$Z_{eff} = \frac{M_{12}c}{\sqrt{\epsilon_r} + 1} \sin \theta$$

where:

M_{12} = transfer inductance between cable sheath and signal wire

c = velocity of light = 3×10^8 m/s

ϵ_r = relative dielectric constant of the cable insulation

$\theta = \omega/c(\sqrt{\epsilon_r} + 1)\ell/2$

ℓ = length of cable

$\omega = 2\pi f$.

To estimate the high frequency response of the aerial T1 cable, a value of 30 pH/m was used as the transfer inductance. This value (30 pH/m) was chosen because the cable has a solid sheath with only one longitudal, overlapped seam. The aperture contribution from this type of cable construction will be quite low. Triple overbraid, which has three layers of cable braid, has a worst case transfer inductance (M_{12}) of 30 pH/m. Since triple overbraid cable has very small aperture area and a DC resistance per meter (2.0 mΩ/m) that closely resembles that of the Aerial T1 cable (1.6 mΩ/m), modeling the effective transfer impedance of the T1 cable by a triple overbraid cable is justified.

The splice case test data reveals that the splice case introduces a huge aperture into the cable. At high frequencies, the transfer impedance test data rises at a rate of 20 dB per decade, due to the effect of the aperture in the cable. This rate of rise is due to the size of the cable apertures, which become quite large when compared to the wavelengths at high frequencies. The transfer inductance (L_t) of the splice case is measured experimentally as 1.6×10^{7} H/m. This value was calculated directly from the test data using the following formula:

$$L_t = Z_t/2\pi f.$$

The splice case provides no shielding for the signal wires, even at frequencies below 10 KHz. The coupling through the splice case will be dominated by the transfer inductance (L_t).

In summary the transfer impedance for the Aerial T1 Cable can be modeled using the formula:

$$Z_t = \frac{R_{DC}\sqrt{j\omega\tau}}{\sinh\sqrt{j\omega\tau}} + j\omega L_t$$

where:

$$L_t = 30 \times 10^{-12} \text{ H/m}$$
$$R_{DC} = 1.6 \times 10^{-3}\ \Omega.$$
$$\tau = \text{diffusion time constant}$$

Because the transfer inductance (L_t) of the splice case is several orders of magnitude greater than that of the cable itself, the first term of the transfer impedance is negligible at high frequencies. Test data support the conclusion that the coupling through the splice case is dominated by the second term. The transfer impedance for the splice case can then be modeled as:

$$Z_t = j\omega L_t$$

where: $L_t = 1.6 \times 10^{-7}$ H/m.

3.4.1 CABLE LOSS EXPERIMENTS

An eight-foot section of Aerial T1 Cable was tested using a network analyzer to determine its common mode insertion loss characteristics. Exhibit 3-9 is a diagram of the test configuration. An AC input signal of 1 V, with a logarithmic frequency sweep betweem 10 kHz to 10 GHz, was applied between the signal wire and sheath. At the far end of the cable, the output voltage was measured and compared with the reference input voltage. The magnitude of the insertion loss over frequency was determined mathematically in decibels (dB) by the analyzer. The basic equation that describes the insertion loss is:

$$I_L = 20 \text{ LOG } (V_{out}/V_{in})$$

where V_{out} is the voltage at the far end of the cable and Vin is the reference voltage input. Exhibit 3-10 is a graph of typical insertion loss of an eight-foot section of cable. The insertion loss falls off at a constant rate, proportional to the square root of the frequency times a loss constant for the cable. The loss constant is determined by the materials used to construct the cable. The insertion loss can be calculated using the following formula:

$$I_L \text{ (dB)} = \sqrt{f} \times \text{(Loss constant)}$$

EXHIBIT 3-9
Cable Loss Test Configuration

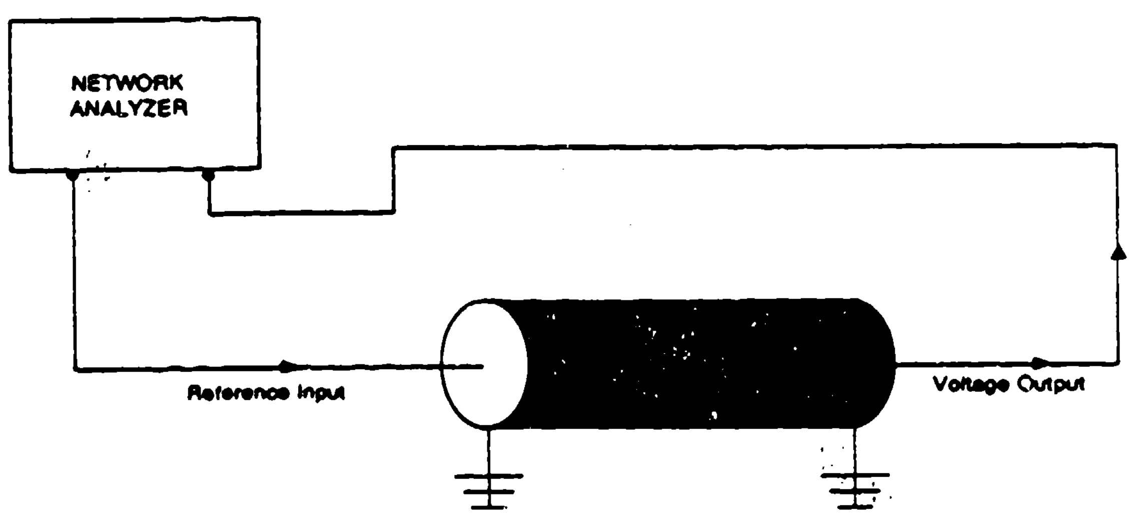
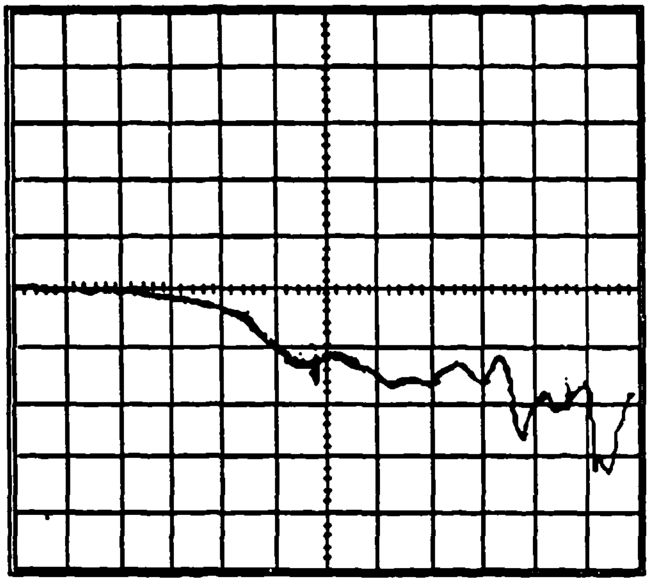
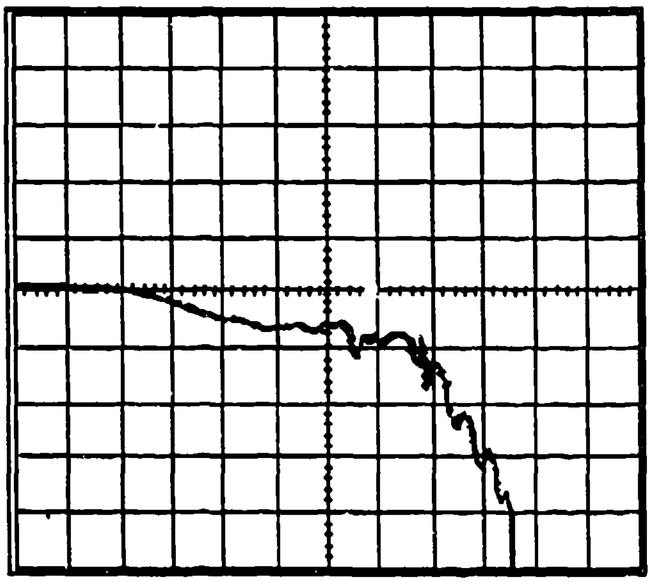


EXHIBIT 3-10
Typical Insertion Loss of an Eight-foot
Section of Aerial T1 Cable without Splice Cases



(a) Red Wire of Orange/Red Pair
Vert = 1 dB / Div
f_c = 10.6 MHz



(b) Red Wire of Orange/Red Pair
Vert = 2 dB / Div
f_c = 35 MHz

The measured data indicate that the Aerial T1 cable has an insertion loss of 3 dB at 10 MHz. Substituting these values into the above equation yields a loss constant of 3×10^{-4} for an eight-foot section of cable. Using this data, the cable loss per foot for any length of cable can be represented by the formula:

$$I_L \text{ (dB)} = (\ell/8)(3 \times 10^{-4})(\sqrt{f})$$

where ℓ is the length of the cable. The cable loss data will be used to determine how much loss EMP-coupled signals will encounter when the pulses propagate down the signal lines.

4.0 DATA ANALYSIS

4.0 DATA ANALYSIS

This section derives the results that were summarized in section 3. Each analysis describes the model that is used, as well as actual and typical parameter values. Conducted transients are estimated using the model and parameter values from the tests. Because no test data on the KHAG 106 cable was available prior to testing, as many cable parameters as possible were determined during this assessment to properly characterize the cable.

To predict the magnitude of EMP energy that will be coupled to the termination devices attached to the T1 cable, a mathematical analysis must be performed based on the test data presented in section 3. The first step in the analysis is to determine the worst case current that will be flowing on the cable sheath. This calculation is based on generally accepted coupling equations and will be calculated in both the time and frequency domains.

The next step in the analysis is to determine the cable coupling effectiveness. This is performed by determining the length of cable which maximizes the induced currents at the equipment.

Since splice cases allow significant HEMP-induced currents to couple to the aerial T1 system, these currents must be calculated and summed with the above results. The splice case transfer impedance data is multiplied by the predicted sheath current to yield a frequency-domain solution. To account for the losses in the T1 cable, the above result is multiplied by the cable loss data. The attenuation over frequency is included in the result because the the cable naturally attenuates signals propagating down the signal wire, due to its transmission line characteristics. For analysis purposes, splice case distances to cable ends were chosen at several distances from the cable ends. The cable loss data was calculated for these specific lengths based upon the experimental loss data. This result was transformed into the time domain to produce a family of pulses, which characterize voltage at the load as a function of the distance from the splice to the load (equipment).

4.1 ANALYSIS OF TDR RESULTS

As seen in Appendix A, the roundtrip time of the TDR pulses is approximately 275 ns. The one-way time is therefore 137.5 ns (275/2). The length of the cable is 102 ft (31.09 m). The propagation velocity of the T1 cable can then be calculated as:

$$\frac{t}{l} = \text{travel time per meter}$$

where:

t = one-way trip time
l = cable length

substituting in the values, we get:

$$\frac{137.5 \text{ ns}}{31.09 \text{ m}} = 4.42 \text{ ns/m}$$

If this pulse were traveling in a vacuum, it would travel at the speed of light (3×10^8 m/s or 3.33 ns/m). The ratio of the propagation velocity in a vacuum to the propagation velocity in the cable is therefore 0.746 (0.746 = 3.33/4.42), or about 75 percent of the speed of light in a vacuum.

The characteristic impedance of a cable is determined using the formula:

$$Z_o = Z_{ref} \frac{(1 + \rho)}{(1 - \rho)}$$

where Z_{ref} = 50 Ω reference impedance of the TDR setup and ρ is the reflection coefficient, as determined by the TDR. ρ is defined as the ratio of the incident pulse to the reflected pulse (E+/E-) and is always between -1 and +1. For a short circuit, $\rho = -1$; for an open circuit, $\rho = +1$.

For the cable without the splice case (sample 1), the wire-to-sheath $\rho = 0.250$. Therefore:

$$Z_o = 50 \frac{(1 + 0.250)}{(1 - 0.250)}$$

$$= 83 \ \Omega$$

As seen in Exhibit 3-1, Z_o was measured to be between 70 Ω and 111 Ω, in close agreement with the calculated value.

For the same cable, the wire-to-wire $\rho = 0.490$. Therefore:

$$Z_o = 50 \frac{(1 + 0.490)}{(1 - 0.490)}$$

$$= 146 \ \Omega$$

Z_o was measured to be between 88 Ω and 120 Ω, reasonably close to the calculated value.

For the cable with a splice case (sample 2), the wire-to-sheath $\rho = 0.220$. Therefore:

$$Z_o = 50 \frac{(1 + 0.220)}{(1 - 0.220)}$$

$$= 78 \ \Omega$$

Z_o was measured to be between 77 Ω and 92 Ω at the cable end and between 101 Ω and 120 Ω at the splice case, again in close agreement with the calculated value.

For the same cable, the wire-to-wire ρ was almost exactly the same as it was for the cable without a splice case ($\rho = 0.490$), so the calculated characteristic impedance was the same as well ($Z_o = 146\ \Omega$).

The measured values of Z_o correspond closely to the calculated values; differences are due to the nonsymmetrical construction of the cable. It is evident that the introduction of the splice case did not change the characteristic impedance of individual wire-to-wire connections, but it did change the characteristic impedance of individual wire-to-sheath connections. These results are summarized in Exhibit 4-1.

EXHIBIT 4-1
Summary of Measured and Calculated Characrteristic Impedances for T1 Cable With and Without Splice Case

Cable	Configuration	Measured Z_o (Ω)		Calculated
		@ cable end	@ splice case	Z_o (Ω)
w/out splice	wire-to-sheath	70 - 111	N/A	83
	wire-to-wire	80 - 120	N/A	146
with splice	wire-to-sheath	77 - 92	101 - 120	78
	wire-to-wire	92 - 122	110 - 135	146

4.2 ANALYSIS OF PULSE TESTING

Pulse current injection testing was performed on two 100 ft samples of KHAG cable. One of the two samples had a PSC splice case installed in line. The test setup configuration is depicted in Exhibit 3-6. The binder wire pairs were terminated into their characteristic impedances, which were determined during TDR testing. The current was measured through the terminations to determine the induced voltages/currents in pre-selected wire pairs.

4.2.1 PULSE TESTING OF CABLE WITH NO SPLICE CASE

The first sample tested was the cable with no splice case (sample 1). A decaying exponential current pulse of 1600 A peak amplitude was injected on the cable sheath; the pulse decayed to $1/e$ in roughly 2.5 μs. The results of the pulse testing are tabulated in Exhibit 4-2. The induced currents, which resembled the incident current pulse with a slower rise time, were measured on individual wires in the cable. This slower rise time is due to current diffusing

EXHIBIT 4-2
Pulse Testing Results of Cable Without Splice Case

Binder	Pair	Wire	Ipeak†
Green	yel/or	yellow	600 mA
Green	yel/or	orange	600 mA
Green	brn/blk	brown	700 mA
Green	brn/blk	black	675 mA
Green	blu/wh	blue	650 mA
Green	blu/wh	white	675 mA
Orange	or/blk	orange	700 mA
Orange	or/blk	black	700 mA
Orange	brn/blk	brown	600 mA
Orange	brn/blk	black	700 mA
Orange	grn/blk	green	700 mA
Orange	grn/blk	black	700 mA
Orange	grn/blk	green, with far end termination shorted	1.3 A‡
Orange	grn/blk	green, through low Z load termination	1.5 A‡
Orange	grn/blk	green, with low Z load terminations at both ends	1.8 A‡

† Ipeak is measured through the noted wire of the twisted pair. This wire is connected to ground through a 75 ohm termination resistor, except where noted otherwise.

‡ This is a non-standard configuration; currents of this magnitude are not expected in actual T1 systems.

through the sheath onto the inner conductors. The diffusion time for a conductive sheath (τ_s) is given by (Reference 5):

$$\tau_s = T^2 \sigma \mu$$

where:

T = sheath thickness = 2.03×10^{-4} m

σ = conductivity (Al) = 3.8×10^{7} ℧/m

$$\mu = \mu_o \mu_r$$

$$= (4\pi \times 10^{-7} \text{ H/m})(1)$$

therefore:

$$\tau_s = 1.96\ \mu s.$$

Because the decay constant of the sheath pulse ($\tau = 2.5\ \mu s$) is very close to the diffusion time constant of the conductive sheath ($\tau_s = 1.96\ \mu s$), the 10%-90% current rise time (τ_r) through Z_o can be approximated by (Reference 5)

$$\tau_r = 0.15\ \mu_s$$

$$= 0.15\ (1.96 \times 10^{-6} \text{ s})$$

$$= 294 \text{ ns}.$$

The internal current and voltage pulses should both rise at about this rate.

The induced load voltage across the termination resistor (V_L) can be calculated using the formula:

$$V_L = \frac{I_o\ R_{DC}}{2}$$

where:

I_o = 1600 A (sheath current)

R_{DC} = 0.050 Ω per 100 ft (measured value).

therefore:

$$V_L = (1600 \text{ A})(0.05\ \Omega)/2$$

$$= 40 \text{ V}.$$

Likewise, the induced current through the termination resistor (I_L) can be calculated using the formula:

$$I_L = \frac{V_L}{Z_L}$$

where Z_L is the load impedance.

therefore:

$$I_L = \frac{40\ V}{75\ \Omega}$$

$$= 533\ mA.$$

The current in the wires in the KHAG cable measured 600-700 mA for terminations typical of standard T1 configurations; currents as high as 1.8 A were measured for twisted pairs with non-standard terminations. The measured values of 600-700 mA agree closely with the calculated value of 533 mA. The pulse shape resembles that of the incident pulse with a slight time shift due to diffusion (see Exhibit 4-3). 600 mA implies a voltage of 45 volts across a characteristic load (75 Ω). Because both ends of each twisted pair are typically terminated with 75 Ω loads, the open circuit voltage V_{oc} is 45 × 2, or 90 volts. The transfer impedance can be calculated using the formula:

$$\frac{V_{oc}}{I_o} = Z_T = R_{DC} + j\omega M$$

If the sheath has imperfections such as apertures or penetrations (i.e. a braided sheath), the imperfections must be modeled as a mutual inductance. Because the sheath for the T1 cable is solid, the $j\omega M$ term is much smaller than the R_{DC} term, and is therefore neglected. Therefore:

$$Z_T = \frac{V_{oc}}{I_o}$$

$$= \frac{90\ V}{1600\ A}$$

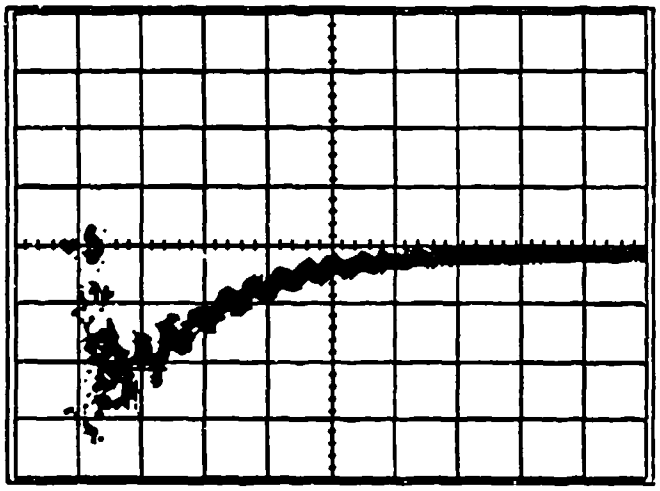
$$= 56\ m\Omega$$

$$= R_{DC}$$

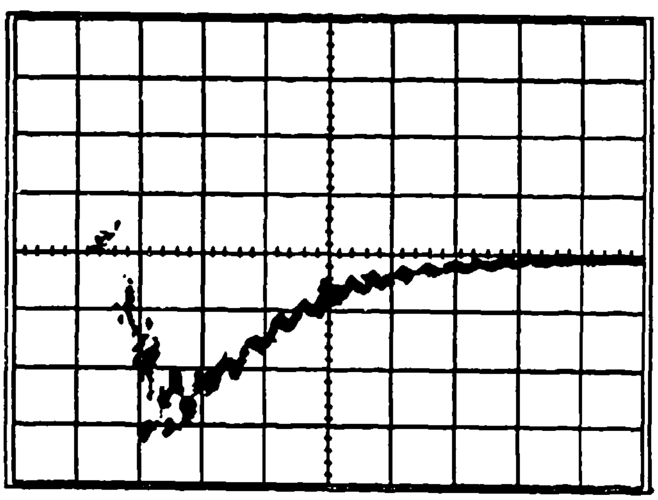
The measured DC value was 50 mΩ (see section 3.2), in close agreement with the calculated value.

However, one must note the rise time of the applied current pulse on the sheath. The test data taken does not accurately depict the rise time of the applied pulse. Estimating the rise time to be in the range of 150-200 ns appears to be reasonable. If the rise time is this slow

EXHIBIT 4-3
Current Injection Results with No Splice Case



Sheath Current (I_o)
Vert = 500 A / Div
Horz = 1 μs / Div



Wire Current through 75 Ω Termination Impedance
Vert = 250 mA / Div
Horz = 1 μs / Div

(t > 100 ns), the early time coupling through the sheath seams due to the transfer inductance may not be significant. The following example illustrates the effect.

$$V_{oc} = I_o Z_T$$

$$= I_o (R_{DC} + j\omega M)$$

$$V_{oc}(t) = I_o(t)(R_{DC} + M\ {}^{di}/_{dt})$$

assuming:

$M = 3 \times 10^{-10}$ H/m (for lapped shields)

$dt = 150$ ns (worst case estimated current rise time)

$di = 1000$ A (arbitrary worst case peak current)

$R_{DC} = 50\ m\Omega$

If we neglect the diffusion component for early times (i.e. $R_{DC} = 0$), then:

$$V_{oc} = M\ {}^{di}/_{dt}$$

$$= (3.0 \times 10^{-10}\ \text{H/m})(1000\ \text{A}) / (150 \times 10^{-9}\ \text{s})$$

$$= 2\ \text{V}.$$

Because V_{oc} is directly proportional to ${}^{di}/_{dt}$, V_{oc} increases as the rise time of the pulse decreases. When the rise time was 150 ns, V_{oc} was only 2 volts, but when the rise time is 50 ns, then:

$$V_{oc} = (3.0 \times 10^{-10}\ \text{H/m})(1000\ \text{A}) / (50 \times 10^{-9}\ \text{s})$$

$$= 6\ \text{V}.$$

If the rise time is actually 50 ns instead of the estimated 150 ns, then the calculated early-time voltage based on the incorrect rise time will be reduced by a factor of 3 (9.5 dB) from the true value. This could be significant if the value of M is large, which may be the case for the splice case model.

Since the value of M (transfer inductance) is assumed to be small for this cable construction type, the results may not be significant. The value of M will be measured during the transfer impedance tests. If it is significantly larger than assumed, the data will have to be extrapolated for early times using the faster rise time as well as the measured value of the transfer inductance.

4.2.2 PULSE TESTING OF CABLE WITH SPLICE CASE

Pulse injection testing was performed on a KHAG T1 cable with a splice case installed in the line (test sample 2). The results of this

testing are tabulated in Exhibit 4-4. An exponential current pulse of approximately 1600 A (I_o) was driven on the cable sheath. The induced voltage/current was measured on signal wires on the various binder groups. Exhibit 4-5 shows the driven pulse and the induced response on a signal wire terminated into its characteristic impedance (75 Ω). The induced signal rings at roughly 2.5 MHz and has a peak to peak amplitude of 10-23 A.

The induced currents on the cable with no splice case were about 600-700 mA per line. The test data indicated that the splice allows the current coupled to the signal wires to increase by a factor of at least 20 dB. Since the resolution of the data recording device was imprecise at fast (early) times, the rise time of the driven pulse (I_o) could not be determined accurately. Estimating it from the raw data, it is believed to be on the order of 150-250 ns. The rise time constraint limits the value of the data taken since the shorter rise time (< 100 ns) is expected on cables in the field. The faster rise time pulse will couple more energy into the cable, since the time derivative of the pulse (dI/dt) will be larger. The dI/dt for a 150 ns pulse is 10.6×10^9, while the dI/dt for a 50 ns pulse is 3.2×10^{10} -- a factor of three (9.5 dB) larger. The ringing could be from the mismatch in the cable at the splice case, the resonant frequency of the splice case, or the quarter-wave frequency of the test cable itself ($\ell = 30.5$ m; $\lambda/4 = 2.5$ MHz). Further studies are proposed where the splice case will be analyzed as a network to characterize its transmission line parameters. From this data an accurate model can be constructed to simulate the coupling through the splice case onto the cable. The transfer impedance of the cable with a splice case will also be measured in order to determine the transfer impedance Z_T, which contains the real and imaginary components R_{DC} and $j\omega M$, where the value of M will be largely affected by the splice case.

4.3 PREDICTED INDUCED LOAD CURRENTS

In this section, the predicted induced currents on the equipment, due to the 50 kV/m Double Exponential pulse (DBEX) threat, are calculated. The analysis is performed by modeling the configuration and response of the T1 KHAG cable using a computer. The results will be a theoretical calculation (based on experimental data) of the survivability of the equipment to HEMP for different configurations of the T1 KHAG cable. The methodology for this analysis has been explained in the introduction; therefore, only the results will be presented in this section.

4.3.1 Induced Sheath Current

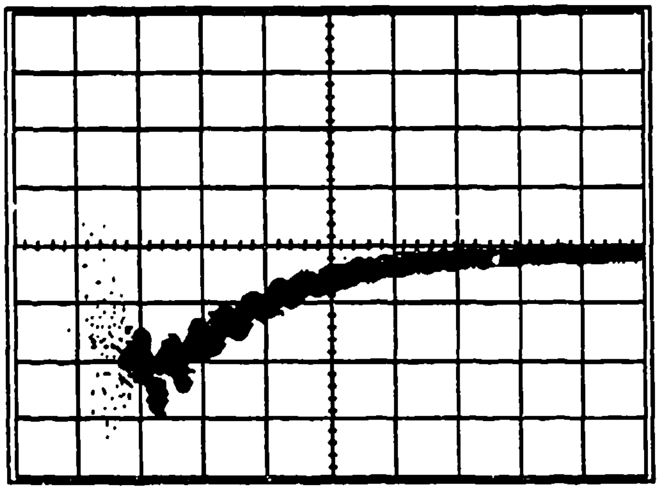
The ultimate goal of the aerial T1 test is to determine the coupled current to the internal conductors of the T1 cable. The amount of current flowing into the equipment can then be calculated, taking into account the attenuation of the signal as it propagates along the inner conductors of the T1 cable. Using EPIC, a computer code developed at Booz, Allen, the current that would couple to the sheath of the T1 cable as a function of frequency can be predicted. This current would be induced by the electromagnetic field produced by a high-altitude nuclear burst.

EXHIBIT 4-4
Pulse Testing Results of Cable with Splice Case

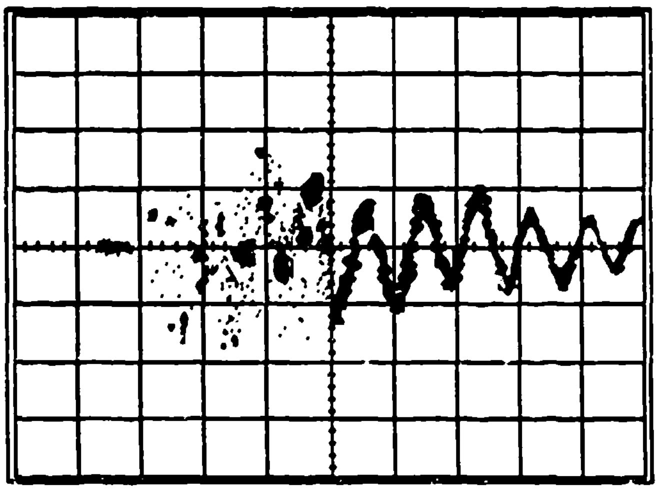
Binder	Pair	Wire	Ipeak†
Blue	or/wh	orange	18
Blue	or/wh	white	15
Brown	or/wh	orange	22
Brown	or/wh	white	21
Blue	or/red	orange	15
Blue	or/red	red	15
Blue	brn/blk	brown	16
Blue	brn/blk	black	16
Brown	or/wh	orange	23
Brown	or/wh	white	15
Brown	blu/blk	blue	20
Brown	blu/blk	black	15
Brown	vio/gry	violet	20
Brown	vio/gry	grey	20

† Ipeak (App) is measured through the noted wire of the twisted pair. This wire is connected to ground through a 75 ohm termination resistor. This configuration is typical of most T1 configurations.

EXHIBIT 4-5
Current Injection Results With Splice Case



Sheath Current
Vert = 500 A / Div
Horz = 1 μs / Div



Wire Current through 75 Ω Termination Impedance
Vert = 5 A / Div
Horz = 0.5 μs / Div

The EPIC code draws heavily on many equations presented in Bell Laboratories' EMP Engineering and Design Principles (Reference 6). To model the EMP response of a lossy line, the following formula is used to calculate the Fourier transform of the EMP electric-field waveform:

$$E(\omega) = \frac{(\beta - \alpha)E_o}{(j\omega + \alpha)(j\omega + \beta)}$$

where $E_o = 5.25 \times 10^4$ volts per meter, $\alpha = 4 \times 10^6$, and $\beta = 4.76 \times 10^8$. The open-circuit-voltage time response of the semi-infinite lossy transmission line to the EMP electric-field is given by the inverse Fourier transform of the product of $E(\omega)$ and the system tranfer function:

$$\begin{bmatrix} V_{oc}^{h}(t) \\ V_{oc}^{v}(t) \end{bmatrix} = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \begin{bmatrix} V_{oc}^{h}(j\omega) \\ V_{oc}^{v}(j\omega) \end{bmatrix} E(\omega) e^{j\omega t} d\omega$$

where:

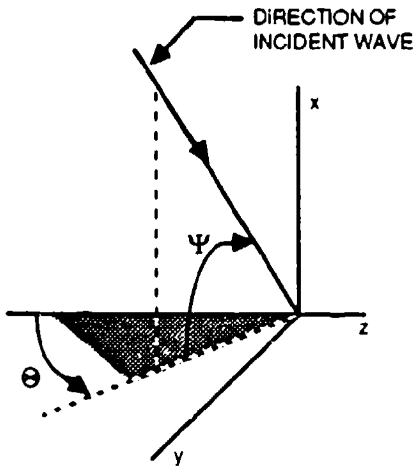
$$V_{oc}^{h}(j\omega) = \frac{c \sin\theta \, (1 + R_h e^{-j\omega T})}{j\omega \, [H(j\omega) - \cos\theta \cos\psi]}$$

and

$$V_{oc}^{v}(j\omega) = \frac{c \sin\psi \cos\theta \, (1 - R_v e^{-j\omega T})}{j\omega \, [H(j\omega) - \cos\theta \cos\psi]}$$

where h and v represent horizontal and vertical polarizations. The angles θ and ψ describe the wavefront's direction of incidence, as shown in Exhibit 4-6.

EXHIBIT 4-6
Definition of Angles θ and ψ With Respect to Incident Wave



R_h represents the ground reflection coefficient for horizontal polarizations:

$$R_h = \frac{\sin\psi - [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2\psi]^{1/2}}{\sin\psi + [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2\psi]^{1/2}}$$

Likewise, R_v represents the ground reflection coefficient for vertical polarizations:

$$R_v = \frac{\epsilon_r(1 + \sigma_g/j\omega\epsilon)\sin\psi - [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2\psi]^{1/2}}{\epsilon_r(1 + \sigma_g/j\omega\epsilon)\sin\psi + [\epsilon_r(1 + \sigma_g/j\omega\epsilon) - \cos^2\psi]^{1/2}}$$

where ϵ is the dielectric constant, σ_g is the conductivity and $\epsilon_r = \epsilon/\epsilon_o$ is the relative dielectric constant of the ground.

The time delay (T_R) between incident and reflected planes of equal phase is given by:

$$T_R = \frac{2h \sin\psi}{c}$$

where h is the average height of the conductors above ground and c is the speed of light.

Losses in the conductors and ground are usually taken into account when calculating the propagation constant for aerial conductors over a real earth:

$$\gamma = \gamma_o H(j\omega)$$

where

$$H(j\omega) = \left[1 + \left\{ \ln \frac{2h}{a_e} \right\}^{-1} \times \left\{ \ln \left[\frac{1 + \beta_1 \sqrt{j\omega}}{\beta_1 \sqrt{j\omega}} \right] + \frac{1}{\beta_2 \sqrt{j\omega}} \right\} \right]^{1/2}$$

and:

$$\beta_1 = h(\mu_o \sigma_g)^{1/2}$$

$$\beta_2 = a_e(\mu_c \sigma_w)^{1/2}$$

and where σ_w is the conductor conductivity, μ_o the permeability of free space, and γ_o ($= jk_o = j\omega/c$) is the propagation constant of a lossless line.

The following assumptions were made when using the EPIC code to assess the current coupling to the sheath:

Length = semi-infinite

$h = 6$ m

$\sigma_w = 1 \times 10^6\ \mho/\mathrm{m}$

$\sigma_s = 1 \times 10^{-2}\ \mho/\mathrm{m}$

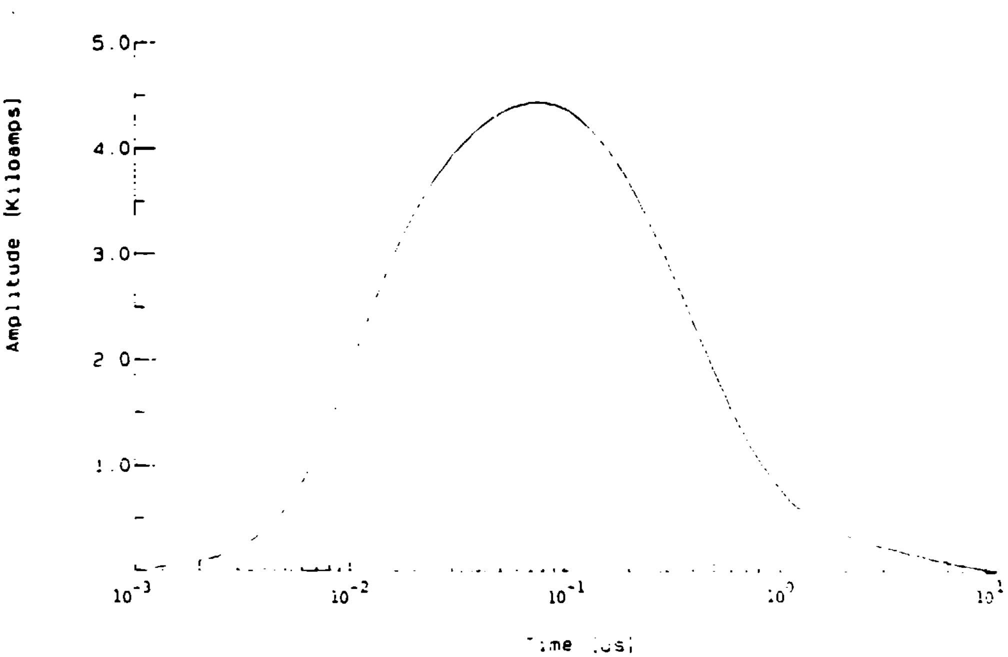
$\psi = 6°$

$\theta = 0°$

$R = 10\ \Omega$

Exhibit 4-7 depicts the coupled sheath currents expected on an aerial T1 configuration. The predicted induced current has a rise time of approximately 100 ns, a peak amplitude of 4.5 kA, and a fall time of 1 μs.

EXHIBIT 4-7
Predicted Threat-level Sheath Currents



4.3.2 Transfer Impedance

A computer program was used to model the experimental transfer impedance. The equations are given section 3. The transfer impedances are shown in Exhibits 4-8 and 4-9 for a splice case and a 100 m long T1 KHAG cable. Note that 100 m has been chosen as the effective length for T1 KHAG coupling to a load. It can be shown that the coupling from the cable more than 100 m from the load will not contribute much to the actual voltage seen by the load. This is because there is an attenuation of at least 26 dB when a signal propagates through 100 m of the T1 cable. Therefore, contributions beyond 100 m can be considered negligible.

4.3.3 Induced Voltage

To calculate the induced voltage (V_{oc}) on the inner conductor, the transfer impedance is multiplied by the sheath current (as determined by EPIC) in the frequency domain. This curve is then Reverse Fourier Transformed to get the curve in the time domain. The voltage induced on the cable is assumed to have no loss within the first 100 m from the equipment. This is considered worst case and is shown in Exhibit 4-10. However for the splice case, it is assumed that the signal coupled into the splice is attenuated as it travels toward the equipment. Exhibit 4-11 shows a typical loss curve for a given length of cable -- 100 m in this case. Therefore, the induced waveform on the splice case was multiplied by the loss at the specified distance from the equipment, before the reverse fourier transform was performed. Exhibits 4-12 through 4-15 present the time waveforms of the voltages due to the splice case.

4.3.4 Induced Current on the Termination Load

Exhibit 4-16 shows the current transmitted to the load as a function of the distance from the splice case to the equipment. This transmitted current is the sum of the coupled currents from a 100 m length of T1 KHAG cable and from the splice case. The current from the splice case will be attenuated as it propagates along the cable from the splice case to the equipment. However, as a worst case scenrio, the current coupled to the first hundred meters of cable is not considered to be attenuated. The induced current on the equipment was determined in section 3 as $V_{oc}(\text{peak})/2R_L$, where $R_L = 75$ ohms.

The peak open circuit voltage is determined from Exhibit 4-10 and Exhibits 4-12 through 4-15. For example, the current induced on the load from current coupled to the splice case is 33 A, with the splice case 30.5 m (100 ft) from the load. In addition, the current induced from the T1 KHAG cable is about 2.7 A. The load, therefore, will experience 35.7 A when a splice case is 30.5 m away. This theoretical calculation is very close to the data obtained experimentally in the pulse testing, assuming the signals are scaled. The curve in Exhibit 4-14 can now be used to determine the placement of the splice case to ensure survivability of the equipment.

EXHIBIT 4-8
Transfer Impedance of Splice Case

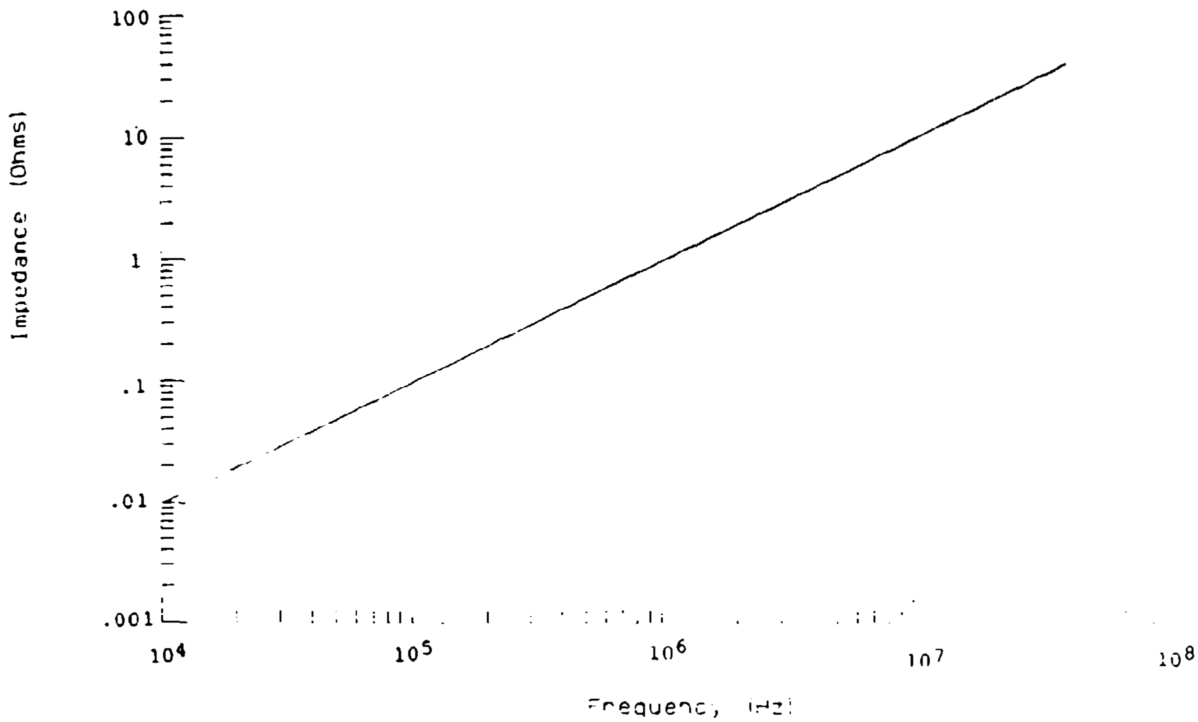


EXHIBIT 4-9
Transfer Impedance of 100 m T1-KHAG Cable

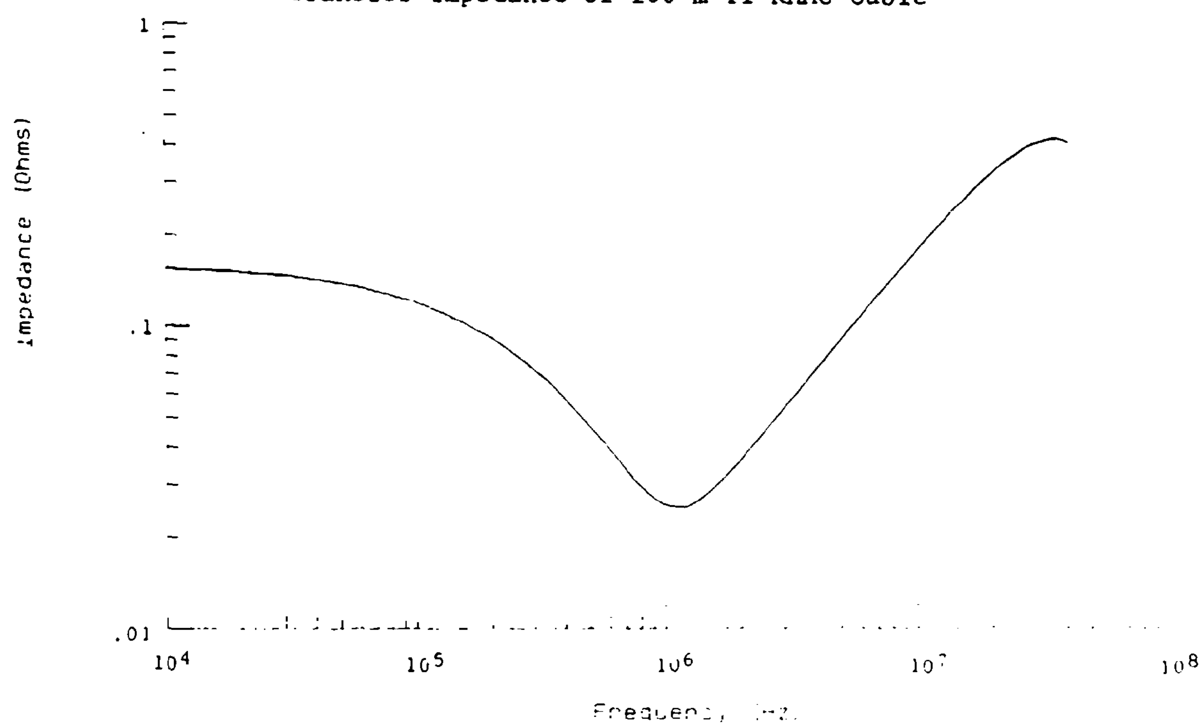


EXHIBIT 4-10
Voltage Induced on 100 m Cable

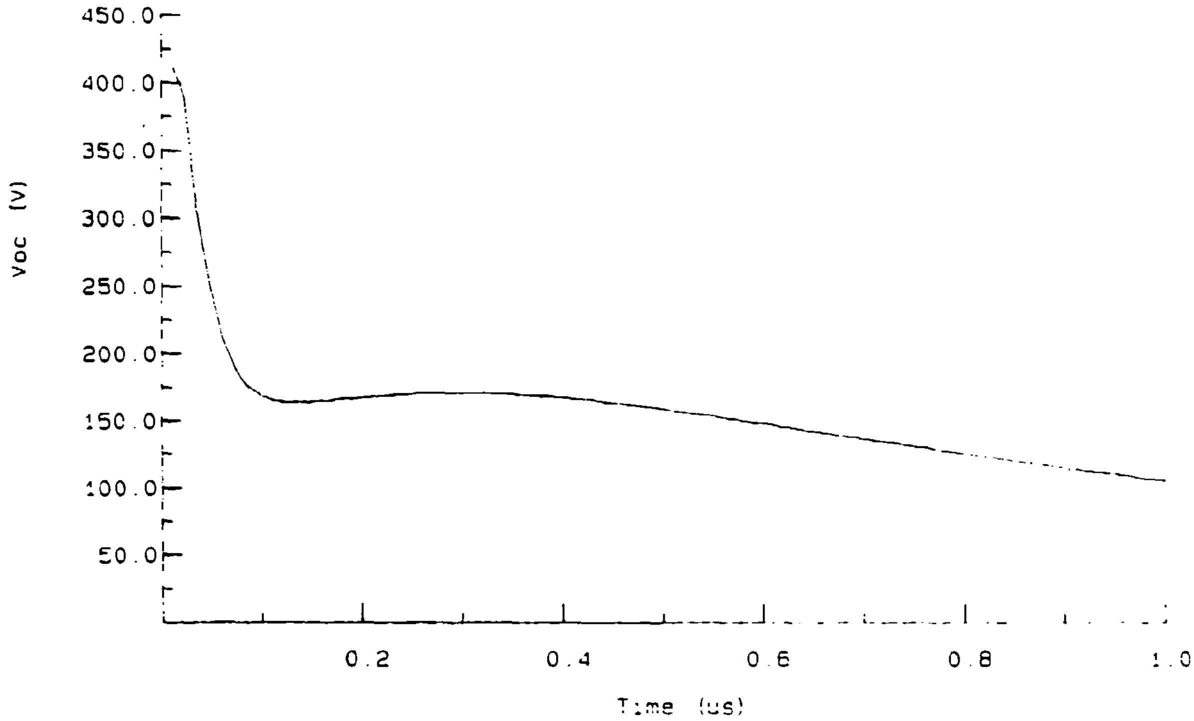


EXHIBIT 4-11
Signal Attenuation of 100 m T1 KHAG Cable

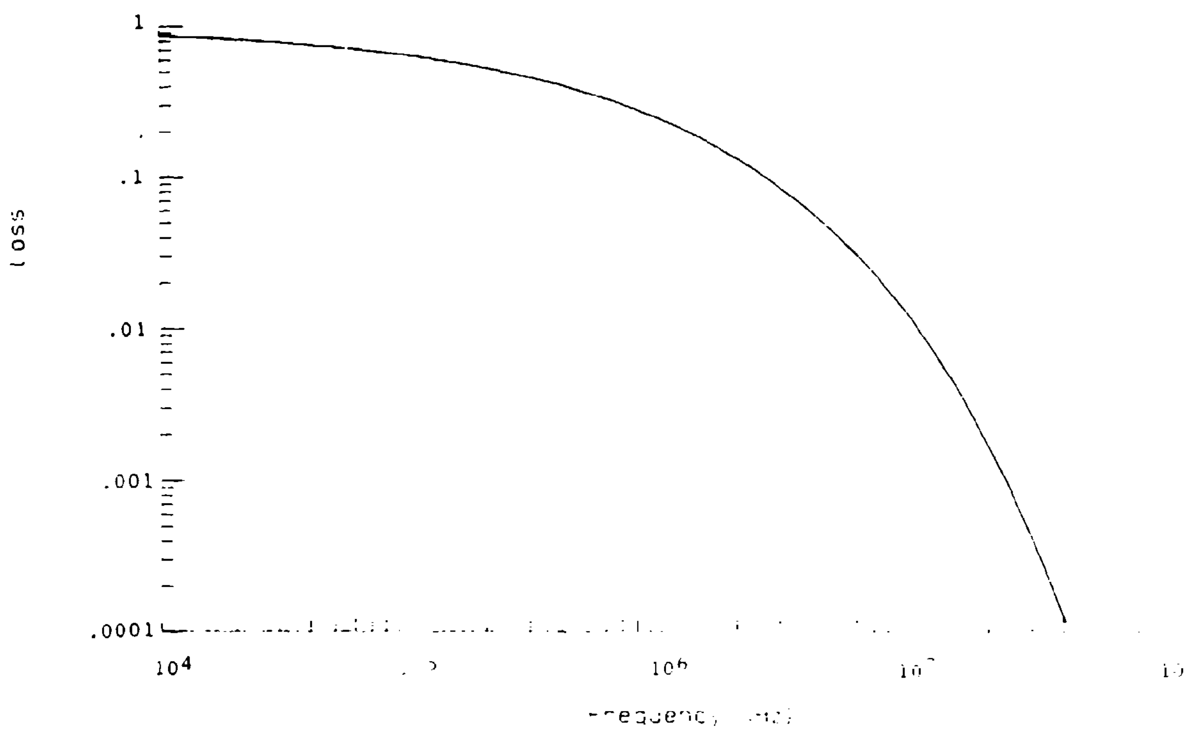


EXHIBIT 4-12
Voltage Induced from the Splice Case

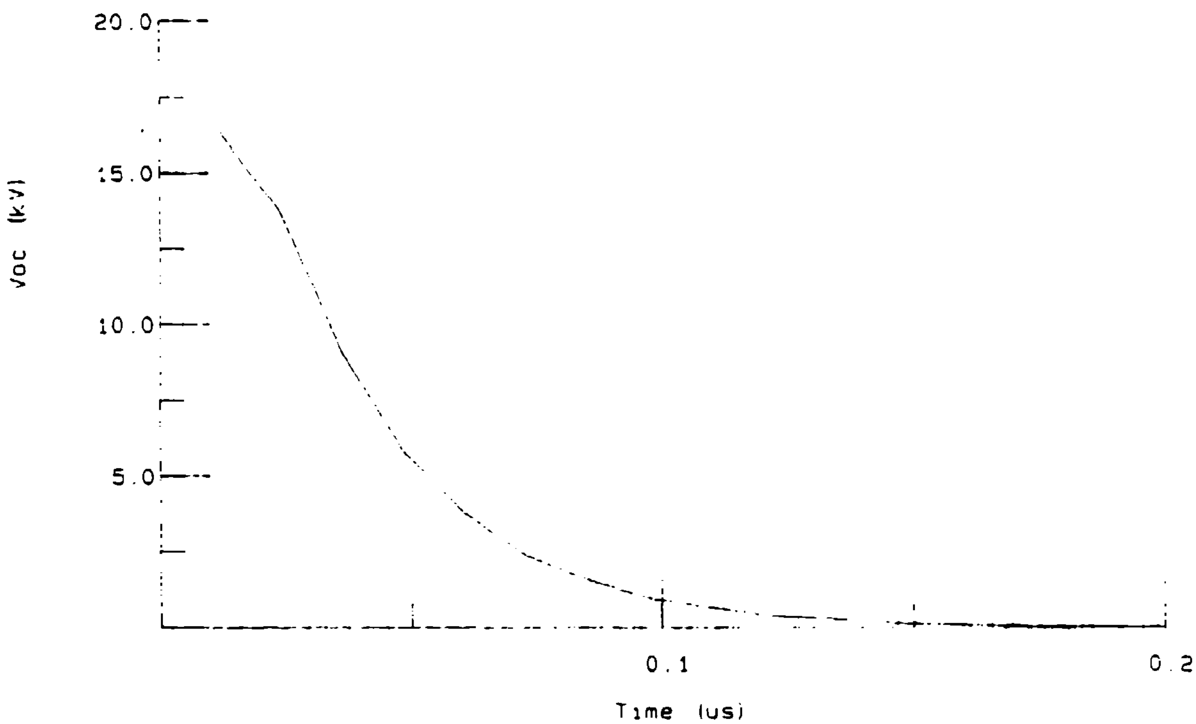


EXHIBIT 4-13
Voltage Induced 30.5 m from Splice Case

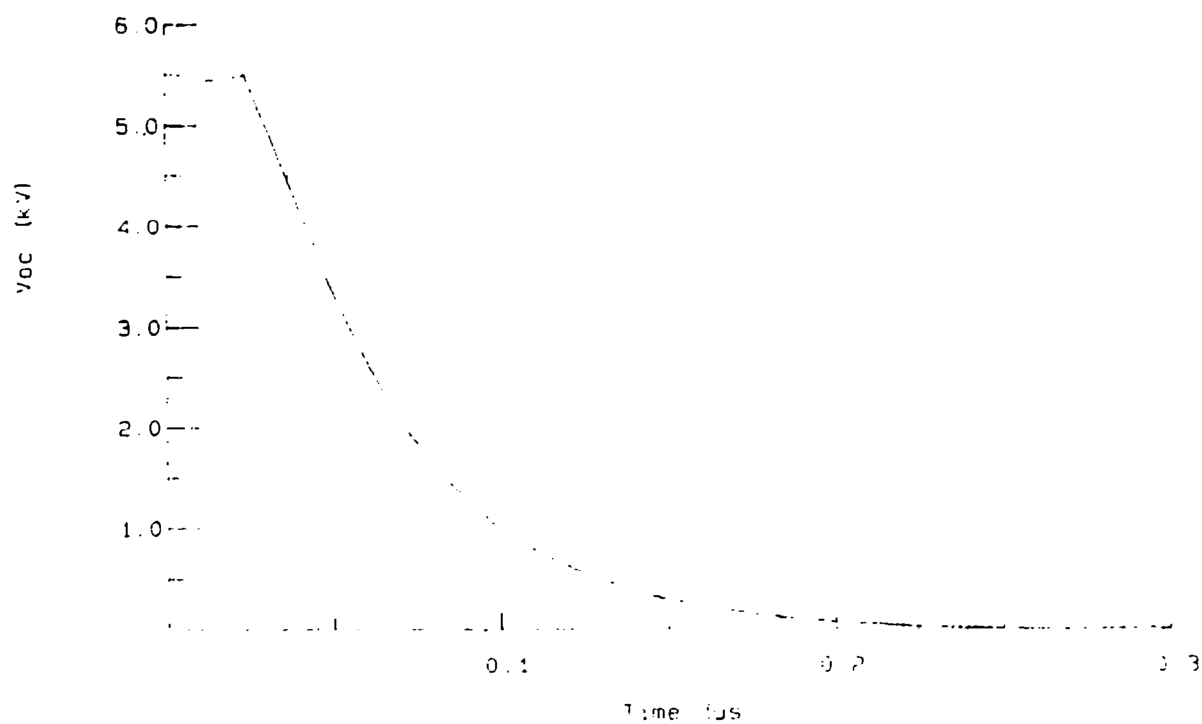


EXHIBIT 4-14
Voltage Induced 100 m from the Splice Case

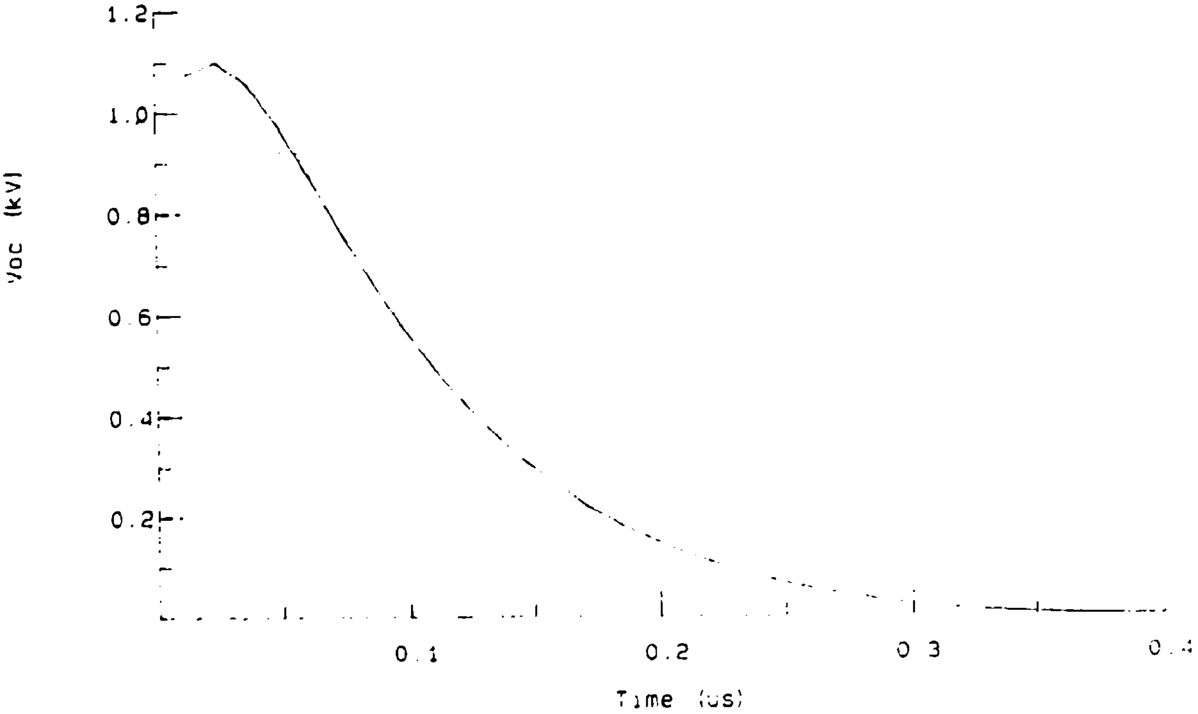


EXHIBIT 4-15
Voltage Induced 200 m from the Splice Case

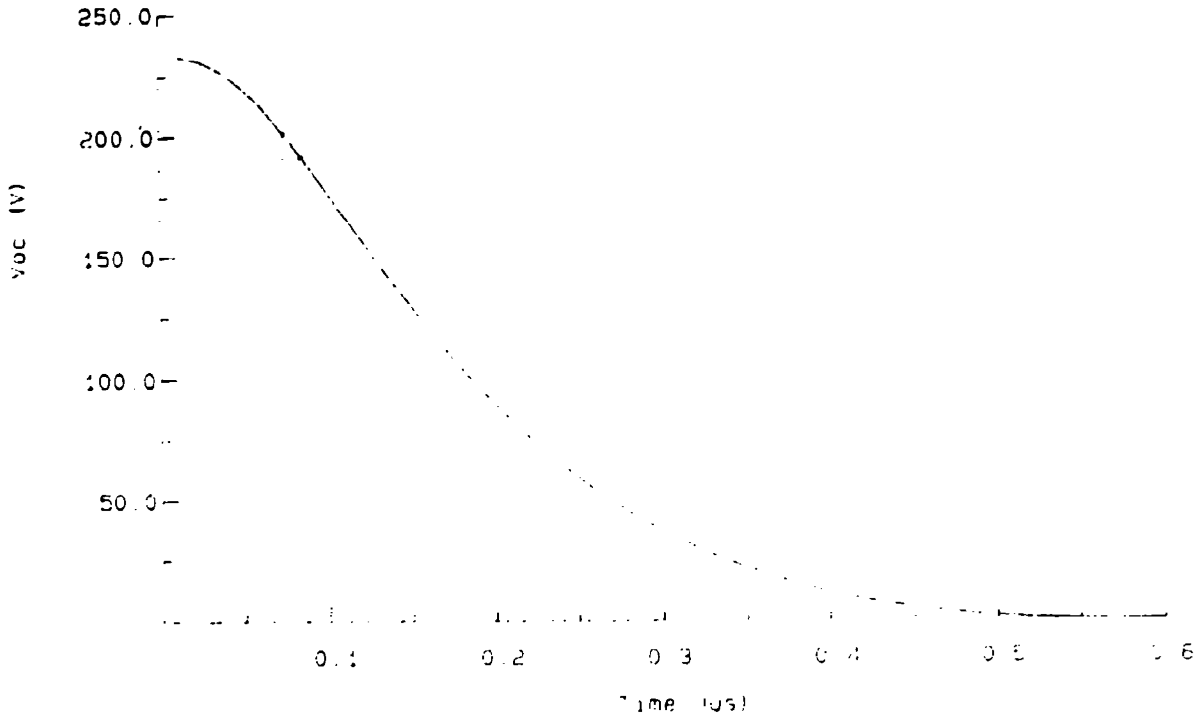
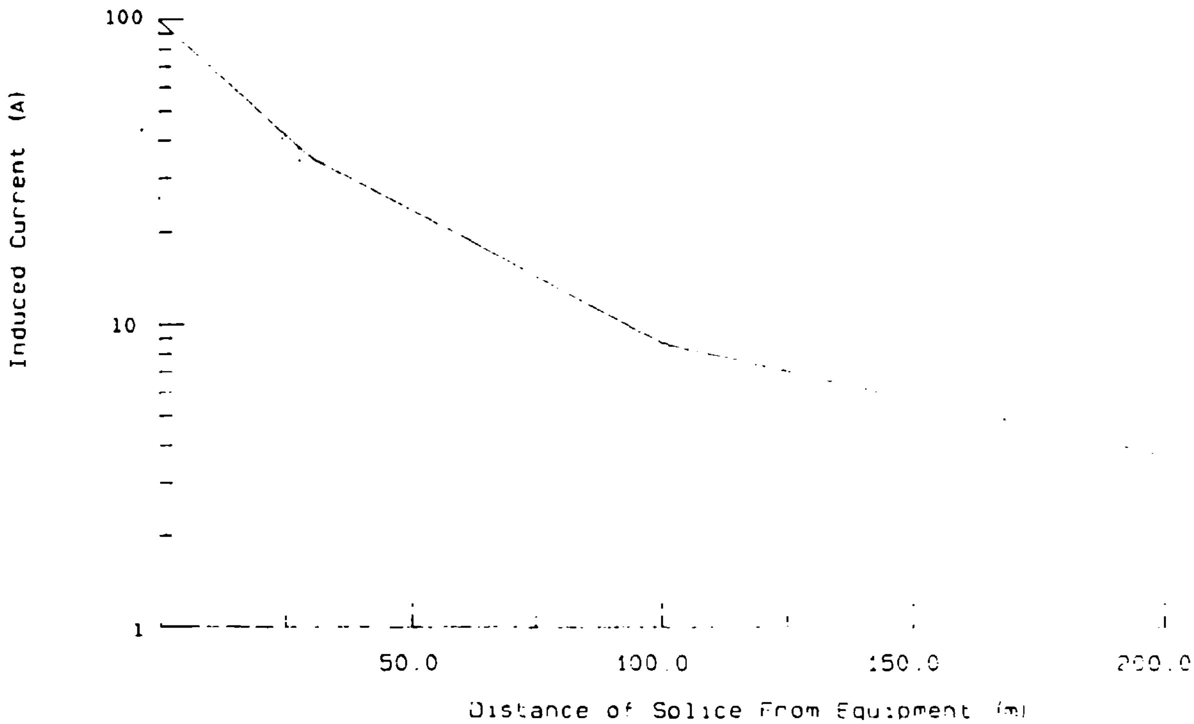


EXHIBIT 4-16
Induced Currents on Equipment from DBEX
Threat Due to Different Splice Locations



5.0 EQUIPMENT THRESHOLDS

5.0 EQUIPMENT THRESHOLDS

To assess the survivability of aerial T1 installations, the results of this cable driving study are used in conjunction with the results of previous test programs, which assessed the survivability of T1 line and CO repeaters as well as D4 channel banks. This section summarizes the specific results of those test programs in a manner suitable for supporting the aerial T1 assessment.

The Buried T1 Carrier Study (Reference 2) describes two series of tests that addressed repeater susceptibility to the effects of these transients: EMP field tests and current-injection tests. The first test, at HDL, used the Army EMP Simulator Operation (AESOP) and Office Sinusoidal Simulator (OSSI) combination to apply simulated-HEMP fields to a 2,000-foot T1 cable with a splice case and pole-mounted repeater at its center. In this test, high-level fields and induced lead currents were simultaneously directed onto the repeater. The second series of tests involved current-injection on signal leads of T1 carrier system components, performed at Bell Labs. Double exponential (DE) and damped sinusoid (DS) pulses were injected.

Tests were performed on a lightning-protected repeater and a special EMP-hardened repeater. Because EMP-hardened repeaters are not used in typical T1 installations, only the lightning-protected repeater tests are discussed in this report.

Based on preliminary results of testing of the D4 channel bank during the T1 Carrier Study, a second study† was undertaken to identify the failure threshold for a D4 channel bank and to identify and verify methods to protect a D4 from EMP-induced transients. This report also focuses on the results of this second study.

5.1 EMP EFFECTS ON LINE REPEATERS

Since T1 signals are digital, and repeaters detect and regenerate rather than amplify them, neither high- nor low-frequency pulse components on signal leads will be amplified and passed along the cable. Therefore, the major concern in repeater susceptibility is whether the circuits will survive when exposed to transients coupled onto signal leads over the one-mile interrepeater lengths.

No failures occurred during the 19 AESOP EMP-simulator field tests of the T1 line repeaters, although outages in equipment operation of 61 μs to 256 ms were experienced. Peak currents of between 1.0 A and 1.4 A were measured at the input leads to the lightning protection [model 208A sealed gas surge limiters (SGSLs)]. However, the peak currents measured at the SGSL outputs were from 1.9 A to 2.2 A, somewhat higher than the input currents. This unusual behavior may have been caused by the nonlinear characteristics of the simultaneous firings of the 20 SGSLs. The current pulses measured at the input leads of the EMP TPDs were relatively slow and broad (2 μs rise time,

† The "EMP Assessment of D4 Channel Bank," a study funded by the OMNCS and administered by DNA under Contract Number DNA001-85-C-0409.

20 μs pulse width). Although it was not explicitly stated in the test report, it is assumed that the pulses measured at the input leads to the SGSLs were similar in rise-time and duration.

During current injection testing of the line repeaters, pulses ranging from 100 to 440 A were injected onto gas tube protected leads of repeater and line fault locate filter equipment; between 11 and 84 A were passed through the protector as a result. Of the 37 units that were tested, three line repeaters failed. A 360 A peak double exponential (DE) current pulse (with a rise-time of about 50 ns) caused the failure of one repeater, with between 38 and 50 A passed through the gas tube to the repeater. A damped sinusoid (DS) current pulse of between 400 and 440 A peak amplitude did not cause any failures, although between 40 and 84 A were passed through the gas tube to the repeater. Two DS current pulses of between 300 and 400 A peak amplitude (with rise-times of about 10 ns) caused the failure of two repeaters, with between 32 and 49 A passed through the gas tubes to the repeaters. These two pulses were the highest DS current pulses injected. Exhibit 5-1 shows a table of equipment failure and nonfailure versus stress levels. The failure threshold of standard gas tube protected T1 line repeaters appears to be between 300 and 400 A for fast rise-time (10-50 ns) pulses.

5.2 EMP EFFECTS ON CENTRAL OFFICE LINE EQUIPMENT

As with line repeaters, terminal equipment is either unprotected or it is protected against lightning and 60 Hz power faults. In a CO, protection may be gas-tube or 3 mil carbon block TPDs. Signal lines entering a building break out of the sheath and run to a Main Distribution Frame (MDF) where the lightning protection is located, then to equipment racks, which contain the office repeaters and channel banks.

Disregarding other office transients and direct coupling to the exposed leads, the currents induced on signal leads at the office would be the same as those at line repeaters. Consequently, tests similar to the line repeater tests were conducted at HDL on CO terminal equipment and on D4 channel banks.

The peak current induced in twisted pair #1 during the AESOP and OSSI combination tests was 223 A. This twisted pair is considered typical of the twisted pairs leading into the CO equipment. While no failures were observed during this phase of testing, none of the test configurations without EMP protection contained a D4 channel bank, which is an integral part of typical T1 systems with VF interfaces. Using these results would therefore lead to an incomplete assessment of the survivability of CO equipment.

Current injection tests of CO repeaters and fault locate filters used special EMP TPDs as protection. Because EMP-hardened equipment is not used in typical T1 CO facilities, these estimates of the survivability of CO equipment are not applicable. In the absence of other data, it is assumed that the damage threshold of the CO repeaters approximates that of line repeaters.

EXHIBIT 5-1
Summary of Current Injection Results

Unit Type Tested	Protection Supplied	Number of Units Tested under Stated Conditions	Test Condition						Results		
			Injection	Pulse Generator	N_2 Pressure	Surge Voltage	Pulse Polarity	Number of Pulses	Input Peak Current Per Wire	Peak Current Protector Passed	Failures
Line	Gas tube	5	Fig. 3 (a)	DE	30 psig	35 kV	+	3-5/sec	100A	11-12A	None
repeater	Gas tube	5	Fig. 3 (a)	DE	30 psig	35 kV	−	3-10/sec	115-150A	15-18A	None
239E	Gas tube	5	Fig. 3 (a)	DS	30 psig	N/A	N/A	6	150-160A	16-21A	None
	Gas tube	4	Fig. 3 (a)	DE	30 psig	35 kV	+	6	280A	40A	None
	Gas tube	4	Fig. 3 (a)	DE	30 psig	35 kV	−	6	280A	40A	None
	Gas tube	4	Fig. 3 (a)	DS	14 psig	N/A	N/A	6	320A	48A	1
	Gas tube	2	Fig. 3 (b)	DE	30 psig	35 kV	+	6	380A	38-50A	1
	Gas tube	2	Fig. 3 (b)	DE	30 psig	35 kV	−	6	400-440A	40-84A	None
	Gas tube	3	Fig. 3 (b)	DS	14 psig	N/A	N/A	6	300-400A	32-45A	1
Line	Gas tube	1	Fig. 4	DE	30 psig	35 kV	+	6	190A	25A	None
fault	Gas tube	1	Fig. 4	DE	30 psig	35 kV	−	6	200A	27A	None
locate	Gas tube	1	Fig. 4	DS	8 psig	N/A	N/A	6	200A	31A	None
filter											
1115XX											

5.3 EMP EFFECTS ON THE D4 CHANNEL BANK

Under the T1 Carrier Study, an EMP-hardened D4 channel bank, enclosed in a shielded cabinet and protected by special TPDs at line interfaces, was subjected to simulated EMP fields and proved to be survivable. However, when the backplate and door of the shielded cabinet were left open, or when either the power or voice frequency (VF) TPDs were removed, hardware within the D4 channel bank suffered permanent failure. Because the equipment failed at the lowest field level (35 kV/m) attainable under the simulator at HDL, it was not possible to determine the actual failure threshold or to evaluate the success of alternative methods of protecting the channel bank.

A second test, therefore, was undertaken to:

- Identify the failure threshold for a D4 channel bank.
- Identify and verify methods to protect a D4 channel bank.

The tests were conducted at the Air Force Weapons Laboratory (AFWL) using the ALECS facility, which produces a vertically-polarized electric field, adjustable in strength from 5 kV/m to 100 kV/m. The simulated EMP had a rise-time of between 3 and 15 ns and a decay-time of about 200 ns, comparable to the waveform expected from an actual EMP. To assess the channel bank's response to the simulator fields, tests of tone transmission, signal transmission, and idle circuit noise were made following each simulator pulse.

This study demonstrated that EMP affects a D4 channel bank primarily through the injection of large current transients at the interfaces to long connecting cables; fields of only 5 kV/m to 10 kV/m are sufficient to cause service-affecting hardware failures of unprotected D4 channel banks. EM fields are also coupled directly to wires on the backplane, but these transients are of a much lower amplitude than those at line interfaces. These transients will only cause damage if the field in the vicinity of the bank exceeds 40 kV/m, and only then if maximum coupling occurs to the backplane wires (i.e. the incident field must be planar and roughly parallel to the backplane wires).

The cables used during the testing of the D4 were typical of those found in many COs. The cables used were:

- Two power cables, each of 6-gauge wire.
- One alarm cable with four pairs of 26-gauge wire.
- Two ABAM 606B shielded T-carrier cables, each with 12 pairs of 22-gauge wire.
- Two VF cables, each with 100 pairs of 26-gauge wire.

The power, alarm, and T-carrier cables were bundled together and were separated horizontally by about six feet from the VF cable bundle.

It was assumed that the currents induced by EMP on cables connected to the D4 channel bank are comparable to those induced on similar cables connected to the 5ESS™ switch†. The maximum current induced on the 128 twisted-pair cables connected to the 5ESS switch was 150 A, so a conservative estimate of 300 A was assumed as the maximum EMP-induced current on the cables connected to the D4 channel bank. At 50 kV/m, the vertical cables connected to the channel bank were adjusted until the current on all but the VF cables reached 300 A. Although 300 A could not be generated on the VF cables, the peak current of 15 A per-pair going into the bank was comparable to the 12 A per-pair expected in a CO environment.

A standard D4 channel bank without any EMP protection was pulsed 25 times at 5 kV/m without recording a single hardware failure. All channel units were tested at this level. An alarm control unit (ACU) was permanently damaged during the one test at the 12 kV/m level, probably resulting from an overcurrent at the power interface. Based solely on this one failure, it was concluded that the failure threshold of an unprotected D4 channel bank is between 5 kV/m and 10 kV/m vertical.

† The 5ESS switch was tested by AT&T for the OMNCS under Contract Number DCA100-85-C-0094.

Exhibit 5-2 summarizes the failure thresholds of a standard, unhardened D4 channel bank in terms of the peak transient current induced at each line interface. For the Alarm, VF, and T-carrier interfaces, the induced currents are for each twisted pair.

EXHIBIT 5-2
Failure Thresholds of Unhardened D4 Channel Bank

Interface	Ip(A)
Alarm	90
VF	3
T-carrier	13-27
Power	37

Further tests measured transient coupling to the backplane wires of the channel bank. The D4 was not connected to any cables other than to a short power cable, protected at the bank interface by a power TPD. To produce maximum coupling, the D4 was configured with no shielding cabinet and was oriented with the backplane wires parallel to the incident field. The D4 was subjected to 3 pulses at 40 kV/m vertical without failure. The same bank (protected on the shelves by EMP plug-in boards) was subjected to one pulse at 80 kV/m, and one channel unit lost its signaling capability. However, when the circuit packs of the channel unit were hardened, no failures were recorded in 3 pulses at the 80 kV/m level. It was concluded that the failure threshold due to direct radiation is between 40 kV/m and 80 kV/m vertical.

Shielding in a CO probably will provide at least a factor of 2 reduction in the incident field level, and the field inside the CO probably will be randomly polarized. The actual failure threshold due to direct radiation, therefore, is probably greater than that predicted above.

In the final test configuration, signal errors or interruptions occurred only twice in 33 tests, with durations of 0.1 ms and 10 ms. A synchronization signal was briefly lost in the remaining 94 percent of the tests, but its duration was not long enough to introduce errors into the data. The effect of these signal interruptions on voice communications was nearly imperceptible, although for data communications at 9600 baud, as many as 100 bits may be lost.

Exhibit 5-3 summarizes the failure thresholds for T1 line repeaters, CO repeaters, and D4 channel bank interfaces. At levels above these thresholds, the components will fail with high probability.

EXHIBIT 5-3
Failure Thresholds for T1 Line Equipment

Component	Failure Current (A)	Risetime (ns)
Line Repeater	300-400	10-50
CO Repeater	300-400	10-50
D4: Alarm	90	~ 70
VF	3	~ 70
T-carrier	13-27	75-85
Power	37	~ 55

6.0 CONCLUSIONS AND RECOMMENDATIONS

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The survivability of typical aerial T1 installations against the HEMP effects has been assessed during a program based on a combination of test and analysis. The major conclusions and the specific test data generated under previous assessments have been used to the greatest extent possible. Where necessary, new test data have been collected to determine the appropriate characteristics of the aerial T1 cable. This section presents the conclusions of this analysis and identifies areas that require further efforts in order to complete this assessment.

The results of this analysis show that the survivability of the D4 Channel Bank equipment is highly dependent on the placement of the splice cases. T1 equipment near a splice case (< 10 m) may see surges of over 100 A. T1 line and Central Office equipment should survive exposure to such transients, but the D4 channel bank appears to be vulnerable to HEMP effects at the Alarm, VF, T-carrier, and Power interfaces. For example, if a splice case is placed 200 m from the equipment, the induced current on the equipment will be about 4 A. In this configuration only the D4 VF Interface will fail. However, if a splice is placed 25 m from the equipment, then the induced current on the equipment will be about 40 A. In this case, the D4 VF, T-carrier and Power Interfaces will fail.

Various issues remain unresolved that could have an impact on the survivability of aerial T1 carrier installations. These issues include:

- The number and placement of splice cases between repeaters or central office equipment. This analysis assumed no synergistic effects, which could limit the applicability of these results.

- The effects of a non-ideal grounding system. The test data were collected using the most ideal ground connections achievable for the test setup. This assessment should be expanded to include appropriate inductances and resistances of real world ground systems.

- Free field simulation testing to determine coupling to the cable typical configurations. The present analysis uses transmission line theory to predict sheath currents; free-field simulation should be used to verify these results. Such free-field simulation should also include investigation of the effects of non-ideal situations, including sheath grounding via guy wires, non-ideal sheath terminations, and multiple splice cases.

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